AD-A056 741 SYSTEMS CONTROL INC PALO ALTO CALIF F/G 17/7

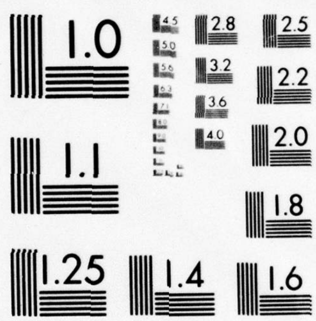
LORAN-C, OMEGA, AND DIFFERENTIAL OMEGA APPLIED TO THE CIVIL AIR--ETC(U)

APR 78 W HEINE, F G KARKALIK, E D MCCONKEY DOT-FA75WA-3662

UNCLASSIFIED FAA/RD-78-30-2 NL

1 OF 3

AD A056741



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD A056741

REPORT NO. FAA/RD-78-30-II

LEVEL III

12

LORAN-C, OMEGA, AND DIFFERENTIAL OMEGA APPLIED TO THE CIVIL AIR NAVIGATION REQUIREMENT OF CONUS, ALASKA, AND OFFSHORE

VOLUME II. ANALYSIS

212p.

W. Heine,
F. G. Karkalik
E. D. McConkey

APR[redacted]78

FINAL REP[redacted]T.

Jul 76 - Dec 77

DOT-FA75WA-3662

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No. FAA-RD-78-30-II	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Loran-C, Omega and Differential Omega Applied to the Civil Air Navigation Requirements of CONUS, Alaska and Offshore - Volume II: Analysis (Vol I - A056740)		5. Report Date April 1978
		6. Performing Organization Code
7. Author(s) W. Heine, F.G. Karkalik, E.D. McConkey		8. Performing Organization Report No.
9. Performing Organization Name and Address Systems Control, Inc. (Vt) 1801 Page Mill Road Palo Alto, CA 94304		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DOT-FA75WA-3662
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590		13. Type of Report and Period Covered FINAL REPORT Period Covering July 1976-December 1977
		14. Sponsoring Agency Code ARD-333
15. Supplementary Notes		

16. Abstract

The objectives of this study were basically twofold. The first was to validate the civil air navigation requirements for CONUS, CONUS Offshore, Alaska, and Alaska Offshore. A requirements matrix was developed to provide a common basis for defining the requirements across all the geographic areas considered. The second basic objective was to assess the capabilities of Loran-C, Omega, Differential Omega, and VLF communications toward meeting the requirements.

Loran-C offers total all-altitude coverage for all geographic regions given existing and proposed chains. The primary drawback is the large area and, hence, number of aircraft affected by single station outage. With suitable redundancy, Loran-C could meet the civil air navigation requirements as a primary or supplementary navigation system in all geographic regions.

Omega lacks adequate coverage over CONUS. Therefore, Omega and Differential Omega are candidates only in Alaska, Alaska Offshore and most of CONUS Offshore. Omega, however, does not meet the accuracy requirements for nonprecision approaches or in high density terminal areas, whereas, Differential Omega is expected to.

The VLF communications system is not dedicated to navigation, hence, reliability becomes an issue. With suitable redundancy the scheduled and unscheduled down

17. Key Words Loran-C, Omega, Differential Omega, Navigation Systems, Navigation Requirements, Civil Aviation, Nonprecision Approach	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	211	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

78 07 26 036

16. Abstract (Continued)

times for maintenance becomes less of a problem. Used in conjunction with Omega signals, the VLF communications signals will provide adequate redundancy and usable geometry.

A potentially significant benefit offered by the candidate systems considered is the support of non-precision approach (NPA) requirements. A separate element of the study, which analyzed all systems considered, was devoted to this topic. Loran-C was found to exceed the NPA requirements in all regions and Differential Omega exceeded them in Alaska, Alaska Offshore and most of CONUS Offshore. The other systems did not meet the NPA requirements including Differential Omega over CONUS.

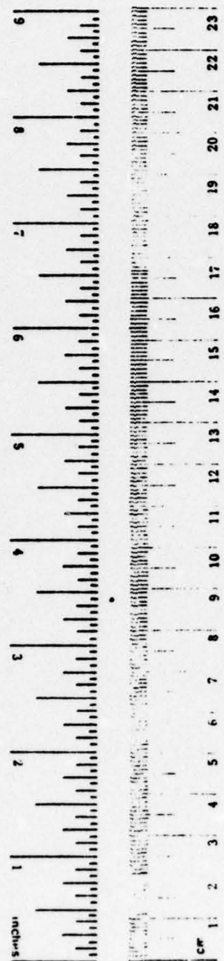
The report is presented in three separate volumes. Volume I presents the executive summary and Volume II presents the detailed technical analysis supporting this summary. Further supportive material is presented in the appendices which make up Volume III.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 [illegible]



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

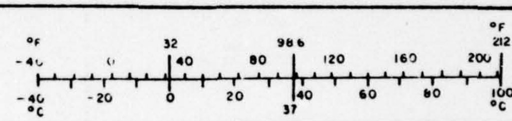


TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	PROGRAM OBJECTIVES AND METHOD OF APPROACH	3
	2.1 Objectives	3
	2.2 Approach	3
	2.2.1 Navigation System Requirements Revalidation	3
	2.2.2 Candidate System Evaluation	4
	2.2.3 Report Organization	6
III.	NAVIGATION SYSTEM REQUIREMENTS	7
	3.1 Requirements Summary	7
	3.2 Coverage	11
	3.2.1 CONUS Coverage	12
	3.2.2 Alaska Coverage	16
	3.2.3 Off-Shore Coverage	17
	3.3 Accuracy	19
	3.4 Operational Considerations	21
	3.4.1 Flexibility	21
	3.4.2 Position Presentation	21
	3.4.3 Common Input Format	22
	3.4.4 Pilot Workload	22
	3.4.5 Failure Alerts	23
	3.4.6 Position Ambiguity Resolution	23
	3.4.7 System Activation and Position Fix Update Rate	24
	3.5 Capacity	29
	3.6 Compatibility	29
	3.7 Reliability	30

IV. LORAN-C SYSTEM EVALUATION 33
4.1 Loran-C Navigation System Description 33
4.1.1 Loran-C Geometry 34
4.1.2 Loran-C Signal Characteristics 37
4.1.3 Avionic Characteristics 43
4.2 Performance Characteristics 47
4.2.1 Coverage 47
4.2.2 Accuracy 53
4.2.3 Operational Considerations 62
4.2.4 Capacity 64
4.2.5 Compatibility 65
4.2.6 Loran-C Reliability/Redundancy 67
4.3 Loran-C in the National Airspace System 76
4.3.1 Implementation Factors 76
4.3.2 Loran-C as the Primary Navigation System. 77
4.3.3 Loran-C as a Supplemental Navigation System 80
V. OMEGA SYSTEM EVALUATION 83
5.1 System Description 83
5.2 Performance Characteristics 93
5.2.1 Coverage 93
5.2.2 Accuracy 99
5.2.3 Operational Considerations 110
5.2.4 Reliability/Redundancy 114
5.3 Omega in the National Airspace System 118
VI. DIFFERENTIAL OMEGA SYSTEM EVALUATION 121
6.1 Differential Omega System Description 121
6.2 Performance Characteristics 124
6.2.1 Coverage 124
6.2.2 Accuracy 136
6.2.3 Operational Considerations 138
6.3 Differential Omega in the National Airspace System 140

VII. VLF COMMUNICATION SIGNALS 141
7.1 VLF Communications Signals System Description . 141
7.1.1 System Status 145
7.2 Performance Characteristics 153
7.2.1 Coverage 153
7.2.2 Accuracy 154
7.2.3 Operational Considerations 154
VIII. NON-PRECISION APPROACH ANALYSIS 157
8.1 Non-Precision Approach Candidate Navigation Systems 157
8.2 Method of Approach 159
8.3 Analysis and Results 166
8.3.1 CONUS Non-Mountainous and Appalachian Region 169
8.3.2 CONUS Mountainous 177
8.3.3 Alaska 194
8.3.4 Additional Factors 198
8.4 Conclusions 198
IX. CONCLUSIONS 201
REFERENCES 207

LIST OF TABLES

		Page
2.1	User Groups Interviewed	5
3.1	Minimum User Aircraft Radio and Radio Navigational Equipment	8
3.2	IFR Navigation System Requirements	9
3.3	Radio-Aided VFR Navigation System Requirements . .	10
3.4	IFR Navigation Requirements (Time to Re-Acquire) .	26
4.1	Loran-C Phase Codes	41
5.1	% Monthly Transmitting Time 1974	116
5.2	Omega % Monthly Transmitting Time 1975	117
6.1	Beacon Selection	126
6.2	Alaskan Beacon Selection	135
7.1	VLF Communications Stations	141
7.2	VLF Station Maintenance Schedule	146
7.3	1976 VLF Comm/Omega Users	149
7.4	1985 VLF Comm/Omega Users	152
8.1	FTE and Airborne Computer Errors	161
8.2	Aircraft Approach Categories	168
8.3	Summary Airport Minima	174
8.4	Summary Airport Ceiling Minima for Mountainous CONUS	182
8.5	Summary Results of Candidate System Estimated Ceilings	188
8.6	Effect of HAT/HAA and Facility Distance on Visibility	189

LIST OF FIGURES

		Page
3.1	Vertical Coverage Requirement for CONUS	13
3.2	CONUS Mountainous and Non-Mountainous Areas	14
3.3	VOR Coverage Gaps at FL180	15
3.4	Alaska Victor Airway Route Structure	18
3.5	Potential Off-Shore Helicopter Operational Areas	20
3.6	Time to Penetrate Route Width Boundary for 45° Route Bend	27
4.1	Loran-C Position Fix Geometry	35
4.2	Typical Loran-C Chain Configuration	36
4.3	Loran-C Pulse	37
4.4	First-Hop Skywave Delay Relative to Groundwave	39
4.5	Loran-C Signal Format	40
4.6	Proposed Loran-C Coverage with the CCZ Chains	49
4.7	Proposed Loran-C Coverage with the CCZ and Mid-Continent Chains	50
4.8	Theoretical Coverage Area for the Caribbean Chain (1500 ft DMRS, 1000 NM Range)	52
4.9	Theoretical Coverage for Extended Gulf of Alaska Chain (1500 ft DRMS, 800 NM Range)	54
4.10	Phase of Secondary Factor with Distance from Source for Various Conductivities (Source: Ref. 21)	56
4.11	Results of Coast Guard Helicopter Flight Test Using Loran-C Navigation	58
4.12	Loran-C Chain Stability Corrections Used at Eglin AFB (Ref.: ADTC-TR-75-54)	61
4.13	Histogram of Loran-C East Coast Chain Off-Air Times	69
4.14	Distribution of the Duration of East Coast Loran-C Off-Air Times (12/75 to 11/76)	70
5.1	Eight Worldwide Stations Providing All-Weather VLF Radio Navigation Information	84
5.2	Omega Signal Transmission Format	85
5.3	Omega Family of Hyperbolic Contours	87
5.4	Multiple Frequency Lane Resolution	88
5.5	Polar Cap Absorption (PCA) Region for Northern Hemisphere	92
5.6	Omega Coverage Prediction for CONUS and CONUS Off-Shore at Noon Midsummer	94
5.7	Omega Coverage Prediction for CONUS and CONUS Off-Shore at Midnight Midwinter	95
5.8	Omega Coverage Prediction for Alaska and Alaska Off-Shore at Noon Midsummer	97
5.9	Omega Coverage Precicition for Alaska and Alaska Off-Shore at Midnight Midwinter	98
5.10	CONUS Omega LOPs for Noon Midsummer	100
5.11	Impact of LOP Crossing Angle on Omega Uncertainty Ellipse	102
5.12	CONUS Omega LOPs CD, DF, DG, and DH	104

5.13 CONUS Omega LOPs for CD, CF, and CH 105
5.14 CONUS Omega LOPs for CD, FG, FH and GH 106
5.15 A-C and D-H LOPs in Alaska 109
6.1 Differential Omega Concept 122
6.2 Differential Omega LF Stations for East Coast Off-Shore Region 127
6.3 Differential Omega LF Stations for West Coast Off-Shore Region 128
6.4 Omega Coverage Prediction for Alaska and Alaska Off-Shore at Noon Midsummer 130
6.5 A-C and D-H LOPs in Alaska 131
6.6 Alaska Off-Shore LF Differential Omega Stations 132
6.7 Alaska LF Differential Omega Stations (150 nmi Radius) 133
6.8 Alaska and Alaska Off-Shore Differential Omega Stations (300 nmi Radius) 134
6.9 Differential Omega Accuracy versus Range from Beacon . 137
7.1 Signal Format for FSK 142
7.2 Signal Format for MSK 144
7.3 Phase Relationships (a) Bit Stream, (b) Frequency Transmitted, (c) Phase Transmitted, (d) Phase at Mixer Output, (e) Recovered Bit Stream 145
8.1 Candidate System TERPS Criteria 163
8.2 Approach Plate for Lincoln Municipal Airport, Lincoln, California 165
8.3 Application of Missed Approach Procedure to Sectional Chart for Lincoln Municipal 167
8.4 Ceiling Histogram for Aircraft Category A 170
8.5 Ceiling Histogram for Aircraft Category B 171
8.6 Ceiling Histogram for Aircraft Category C 172
8.7 Ceiling Histogram for Aircraft Category D 173
8.8 Ceiling Histograms for Iowa Airports 175
8.9 Current NPA Ceiling Minimum Histogram for Category A Aircraft in CONUS Mountainous Region 178
8.10 Current NPA Ceiling Minimum Histogram for Category B Aircraft in CONUS Mountainous Region 179
8.11 Current NPA Ceiling Minimum Histogram for Category C Aircraft in CONUS Mountainous Region 180
8.12 Current NPA Ceiling Minimum Histogram for Category D Aircraft in CONUS Mountainous Region 181
8.13 Candidate System Estimated Ceiling Minima Histogram for Category A Aircraft in CONUS Mountainous Region . . . 183
8.14 Candidate System Ceiling Estimated Minima Histogram for Category B Aircraft in CONUS Mountainous Region . . . 184
8.15 Candidate System Ceiling Estimated Minima Histogram for Category C Aircraft in CONUS Mountainous Region . . . 185
8.16 Candidate System Ceiling Estimated Minima Histogram for Category D Aircraft in CONUS Mountainous Region . . . 186
8.17 Histogram of Ceiling Minima Reduction for Aircraft Category A 190
8.18 Histogram of Ceiling Minima Reduction for Aircraft Category B 191

8.19 Histogram of Ciling Minima Reduction for Aircraft Category C 192
8.20 Histogram of Ceiling Minima Reduction of Aircraft Category D 193
8.21 Histograms of Current NPA Ceiling Minima in Alaska . . 195
8.22 Histogram of Estimated NPA Ceilings for Candidate Navigation Systems in Alaska 196
8.23 Histograms of Estimated NPA Ceiling Reductions in Alaska 197

I. INTRODUCTION

Volume II is the second of three volumes entitled, "Loran-C, Omega, and Differential Omega Applied to the Civil Air Navigation Requirements of CONUS, Alaska and Offshore." This volume presents the detailed analysis supporting the executive summary of Volume I. For convenience, the format of Volumes I and II are identical. The study objectives and the methodology used to achieve these objectives are the subject of Section II of this volume. Section 2.2.3 presents the organization of the remainder of the report. Supportive documentation is presented in Volume III in the form of appendices.

II. PROGRAM OBJECTIVES AND METHOD OF APPROACH

2.1 OBJECTIVES

The primary objective of the study discussed in this report is to evaluate Loran-C, Omega, Differential Omega and the VLF Communications system, as to their ability to support the current and future domestic air navigation requirements. For this study, the region of applicability includes CONUS, CONUS Off-shore, Alaska and Alaska Offshore. The Loran-C system is evaluated as both primary and supplementary systems in these regions and the other systems are evaluated as supplementary systems only.

The primary objective can be achieved by establishing secondary objectives which will permit a more systematic methodology to be implemented. Two secondary objectives have been established, these are: (1) revalidate the navigation system requirements and (2) evaluate the candidate systems as they relate to the navigation requirements. With these secondary objectives it is possible to subdivide the study into two sequential phases in which the first phase addresses the navigation requirements evaluation and the second phase addresses the system evaluation. The method of approach for these two phases is discussed in the following section.

2.2 APPROACH

2.2.1 Navigation System Requirements Revalidation

Revalidation of the navigation requirements involves, as an initial step, gathering all current information pertaining to this particular subject. The information gathering process was begun with a literature search and ultimately ended with personal interviews with cognizant personnel. The documents considered in the literature search are Referenced [1] through [16].

Personal interviews were conducted with the Federal Aviation Administration Headquarters and Regional Offices and with the user groups listed in Table 2.1.

Subsequent to the interviews, navigation system requirements categories were established. Quantification of the requirements in each category was attempted using the information gathered from the literature and interview surveys. Where insufficient information existed for quantification, an attempt was made to specify quantities with reasonable justification. The end product is a complete quantification of the requirements in the four regions of concern - CONUS, CONUS Off-shore, Alaska and Alaska Off-shore.

2.2.2 Candidate System Evaluation

The candidate system evaluation was performed through an extensive literature search for each of the candidate systems. The documents used for reference are listed in each of the Sections corresponding to a particular navigation system and, hence, are not repeated here. Where insufficient data was available in the documentation an analysis was performed to derive the data necessary for system requirements evaluation. This is specifically true of the non-precision approach analysis which addressed the candidate navigation system capability to meet the non-precision approach requirements.

The evaluation process was performed in a format similar to the navigation requirements such that comparison between the system performance characteristics and system requirements could be readily accomplished. The evaluation process concluded with an evaluation of the ability of each system to meet the requirements and an assessment of implementation factors. The next section discusses the organization of the report.

Table 2.1

User Groups Interviewed

Air Transport Association
National Pilots Association
Helicopter Association of America
Aircraft Owners and Pilots Association
National Business Aircraft Association
Experimental Aircraft Association
Alaska Air Carriers Association
Alaska Airlines
Wien Air Alaska
Reeve Aleutian Airlines
Evergreen Helicopter of Alaska
Sea Airmotive
Winship Air Service
ARCO
Petroleum Helicopters, Inc.
Attendees of the HAA IFR Helicopter Offshore/ Remote Area Navigation Conference, June 30 - July 1, 1976, New Orleans, Louisiana

2.2.3 Report Organization

Section III presents the navigation system requirements. The requirements categories representing individual subsections of Section III, include coverage, accuracy, operational considerations, capacity, compatibility and reliability. The four candidate navigation systems, Loran-C, Omega, Differential Omega and VLF communications are the subjects of Section IV, V, VI and VII respectively. Since the non-precision approach analysis was quite extensive it is presented separately in Section VIII. Section IX presents specific study conclusions. Backup material is presented in three appendices contained in Volume III.

III. NAVIGATION SYSTEM REQUIREMENTS

This section presents the civil air navigation requirements in the form of tables and an associated description of the table elements. The requirements pertain to two primary user classifications:

(1) "IFR," which is defined as operation under Instrument Flight Rules (IFR) under either Instrument Meteorological Conditions (IMC) or Visual Meteorological Conditions (VMC); and

(2) "Radio-aided VFR," which is defined as Visual Flight Rules (VFR) operation under VMC which is not solely dependent upon pilotage.

"Radio-aided VFR" is defined to span between the IFR user, who is totally dependent upon the radio navigation system in VMC, and the VFR user who can navigate purely from pilotage. This classification stems from those user groups who lack adequate visual references for solely VFR pilotage, as exhibited by flights over homogeneous terrain, operations over water, and night VFR. For reference, the minimum user aircraft navigation equipment according to the Federal Aircraft Regulations (FAR) is shown in Table 3.1.

3.1 REQUIREMENTS SUMMARY

The navigation system requirements for the IFR user are summarized in Table 3.2 and for the radio-aided VFR user in Table 3.3. The tables present the requirements according to flight phase, terrain characteristics, and traffic density. Three flight phases are considered: (1) enroute; (2) terminal area, including transition from enroute to the capture of precision approach aids or the initiation of non-precision approach procedures; and (3) non-precision approach.* The enroute flight

* This report does not address precision approach, the procedures for which are specified in [4].

Table 3.1

Minimum User Aircraft Radio and Radio Navigational Equipment

USER	FAR PART NUMBER	IFR	VFR
General Aviation	91[(1)]	Two-way radio communications and navigation equipment appropriate to the ground facilities to be used.	Compass, airspeed indicator, and altimeter.
Air Taxi	135[(2)]	One communications transmitter, two receivers for navigation and two receivers for communications.	Two-way radio communications and navigation equipment to receive radio signals from the ground facilities to be used.
Air Carrier	121[(3)]	One communications radio, two independent receivers for meteorological information, two independent systems to receive radio navigational signals from all primary enroute and approach navigational systems intended to be used; only one landing system is required.	

Table 3.2

IFR Navigation System Requirements

USER	FLIGHT PHASE	REGION	COVERAGE						ACCURACY (2D)	OPERATIONAL							CAPACITY	COMPATIBILITY	SIGNAL RELIABILITY
			CONUS		ALASKA		OFF-SHORE			FLEXIBILITY	POSITION PRESENTATION	COMMON INPUT FORMAT	PILOT WORKLOAD	FAILURE ALERTS	POSITION RESOLUTION AMBIGUITY	TIME TO RE-ACQUIRE			
			VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL											
IFR	ENROUTE	NON-MOUNTAINOUS	2000 AGL TO FL 600	TOTAL	2000 AGL TO FL 600	TOTAL	500 AGL TO 10,000 MSL	200 NMI OFF-SHORE	±4 NMI 95%	YES (5)	COURSE DEVIATION, NMI (6) ρ/θ LAT/LON	YES	(7)	MUST BE AVAILABLE	LESS THAN 0.5% OF THE TIME	1-2 MIN	UN-LIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
		MOUNTAINOUS	2000 AGL TO FL 600	(1)	2000 AGL TO FL 600	TOTAL	NOT APPLICABLE	NOT APPLICABLE	±4 NMI 95%	YES	COURSE DEVIATION	YES	(7)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.5-1 MIN	UN-LIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
	TERMINAL	HIGH DENSITY	200 AGL TO 14,500 MSL	(2)	200 AGL TO 14,500 MSL	(2)	200 AGL TO 10,000 MSL	(2)	(4,9) ±2 NMI 95%	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.25-0.5 MIN	UN-LIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
		LOW DENSITY	200 AGL TO 14,500 MSL	(2)	200 AGL TO 14,500 MSL	(2)	200 AGL TO 10,000 MSL	(2)	(9) ±4 NMI 95%	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.5-1 MIN	UN-LIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
	NON-PRECISION APPROACH		250 AGL TO 14,500 MSL	(3)	250 AGL TO 14,500 MSL	(3)	250 AGL TO 10,000 MSL	(3)	±1.5 NMI	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.25 MIN	UN-LIMITED	AS PER PREVAILING SPECS	FAIL-SOFT

(1) Equivalent to current and increasing with time to reflect projected traffic density increases.
(2) All terminal areas being serviced currently and those projected to be serviced.
(3) All airports currently with non-precision approach procedures and those where such procedures are expected to be required.
(4) 3D - ±2.0 NMI, 4D - ±.15 NMI
(5) Not a hard requirement, but does have significant cost impact.
(6) Enroute preplanned direct only.
(7) Less than or equal to single waypoint VORTAC-based RNAV system.
(8) Less than or equal to dual waypoint VORTAC-based RNAV system.
(9) ±2 NMI in terminal maneuvering area (within 15 NMI of airport) ±4 NMI beyond 15 NMI from the airport.

Table 3.3

Radio-Aided VFR Navigation System Requirements

USER	FLIGHT PHASE	REGION	COVERAGE						ACCURACY	OPERATIONAL CONSIDERATIONS	CAPACITY	COMPATIBILITY	RELIABILITY
			CONUS		ALASKA		OFF-SHORE						
			VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL					
VFR	ENROUTE	NON MOUNTAINOUS	2000 AGL TO FL600	TOTAL	2000 AGL TO FL600	SEE FIG. 3.	500 AGL TO 10,000 AGL	SEE FIG. 3.	LESS THAN OR EQUIV-ALENT TO IFR	LESS THAN OR EQUIV-ALENT TO IFR	UNLIMITED	AS PER PREVAILING SPECS.	LESS THAN OR EQUIV-ALENT TO IFR
		MOUNTAINOUS	2000 AGL TO FL600	(1)	2000 AGL TO FL600	SEE FIG. 3.	500 AGL TO 10,000 AGL	SEE FIG. 3.					

(1) Equivalent to current coverage and increasing with time to reflect projected traffic density increases.

phase is divided into non-mountainous and mountainous regions, and the terminal flight phase is divided into high density and low density regions.

The navigation system requirements are presented in six requirement categories. These categories are coverage, accuracy, operational considerations, capacity, compatibility and signal reliability. The categories are, in several instances, broken down into subcategories. Coverage is separated into vertical coverage and horizontal coverage for three regions: CONUS, Alaska, and off-shore. Eight subcategories exist under operational considerations. These are flexibility, position presentation, input format, pilot workload, failure alerts, position ambiguity resolution, and system activation.

Wherever possible, the navigation system requirement is quantified. Where quantification is impossible a qualitative specification is made. To the greatest extent practical, requirements specifications are based on published information. The detailed assumptions and rationale behind these specifications are discussed in the remaining subsections of Section III, according to the requirement categories and subsection cross-reference presented in Table 3.2.

3.2 COVERAGE

In this section, the coverage requirement is specified for the three regions of interest: CONUS, Alaska, and off-shore. The coverage in each region is subdivided into two dimensions, vertical and horizontal. Requirements relating to each dimension will be specified independently. The vertical dimension does not imply a 3D capability, but that the navigation signals must be available at the various flight levels as indicated for each flight phase. The three regions are discussed individually with reference to the IFR user and the VFR user, as appropriate.

3.2.1 CONUS Coverage

3.2.1.1 Vertical Coverage. For the enroute flight phase, the IFR and VFR navigation coverage requirement, as illustrated in Figure 3.1, includes the region from the floor of controlled airspace (2000 AGL) to FL600. Vertical coverage in both high and low density terminal areas includes the airspace from 200 AGL to 14,500 MSL. The 200 AGL arises from the lowest minimum ceiling achievable for Category I precision landing aids. Although these landing aids are usually captured at higher altitudes, the 200 AGL lower limit provides coverage for capture at any altitude at or above the ceiling minimum and for missed approach guidance. The upper limit of 14,500 MSL corresponds to the upper boundary of the control zones which underlie the continental control area. Terminal areas not associated with control zones are considered a part of the enroute requirement. The vertical coverage for non-precision approaches is comparable to the terminal flight phase coverage requirements. The TERPS [4] document specifies the lowest minimum descent altitude (MDA) for non-precision approach procedures as 250 feet above the controlling obstacle. Hence, coverage to 250 AGL will provide the coverage necessary for non-precision approaches.

It should be noted that the terminal area and non-precision approach vertical requirements relate specifically to the IFR user, since the VFR user may operate only when visual references are available during these flight phases.

3.2.1.2 Horizontal Coverage. The IFR and VFR horizontal coverage requirement for the enroute flight phase is highly geographic-region-dependent. For the non-mountainous regions the horizontal coverage is specified as "total." This corresponds to the unshaded region of Figure 3.2. In the mountainous regions, charts displaying areas where terrain precludes current navigation support, at various flight altitudes, indicate the horizontal enroute coverage requirement [5]. Figure 3.3 indicates an example

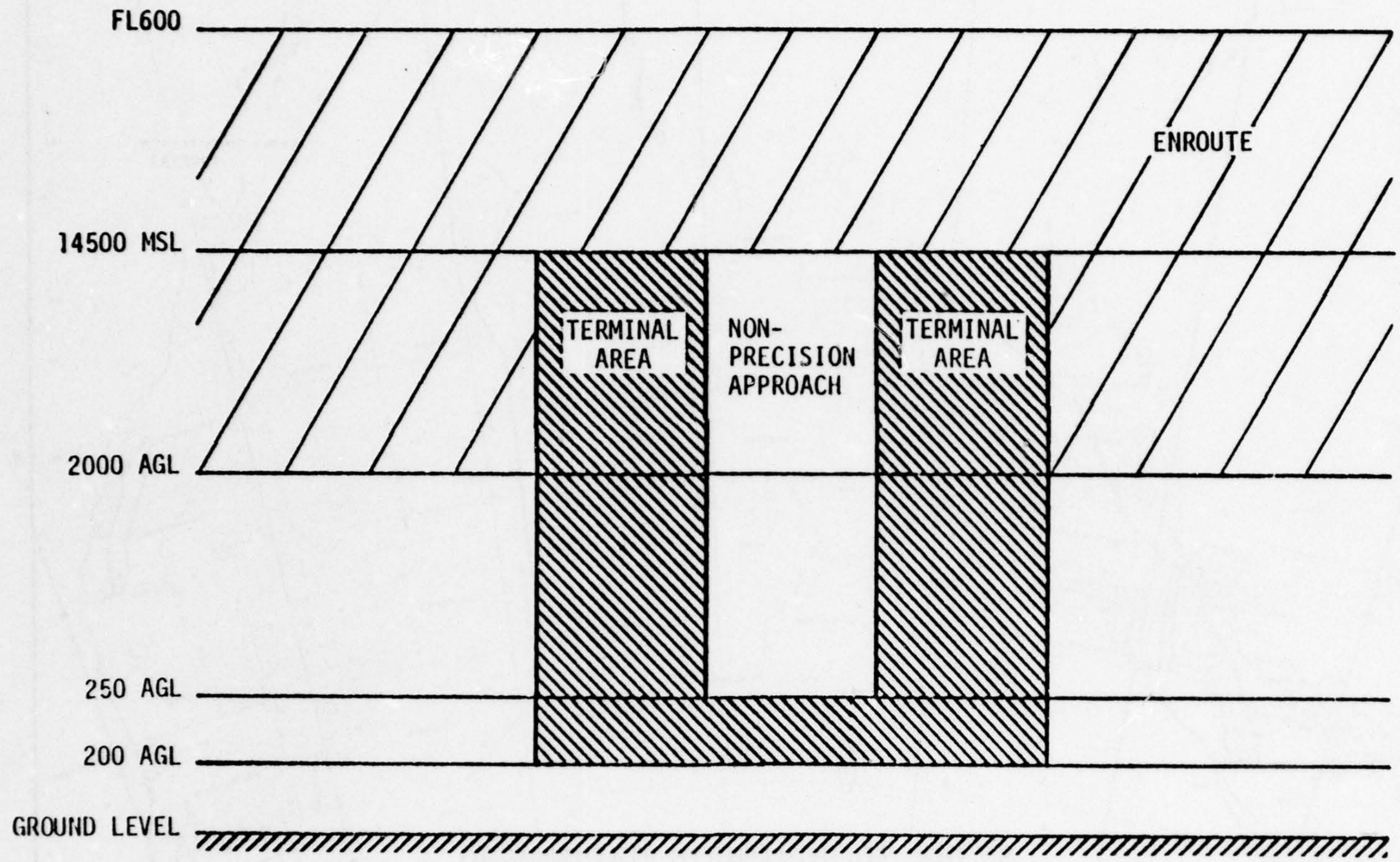


Figure 3.1 Vertical Coverage Requirement for CONUS

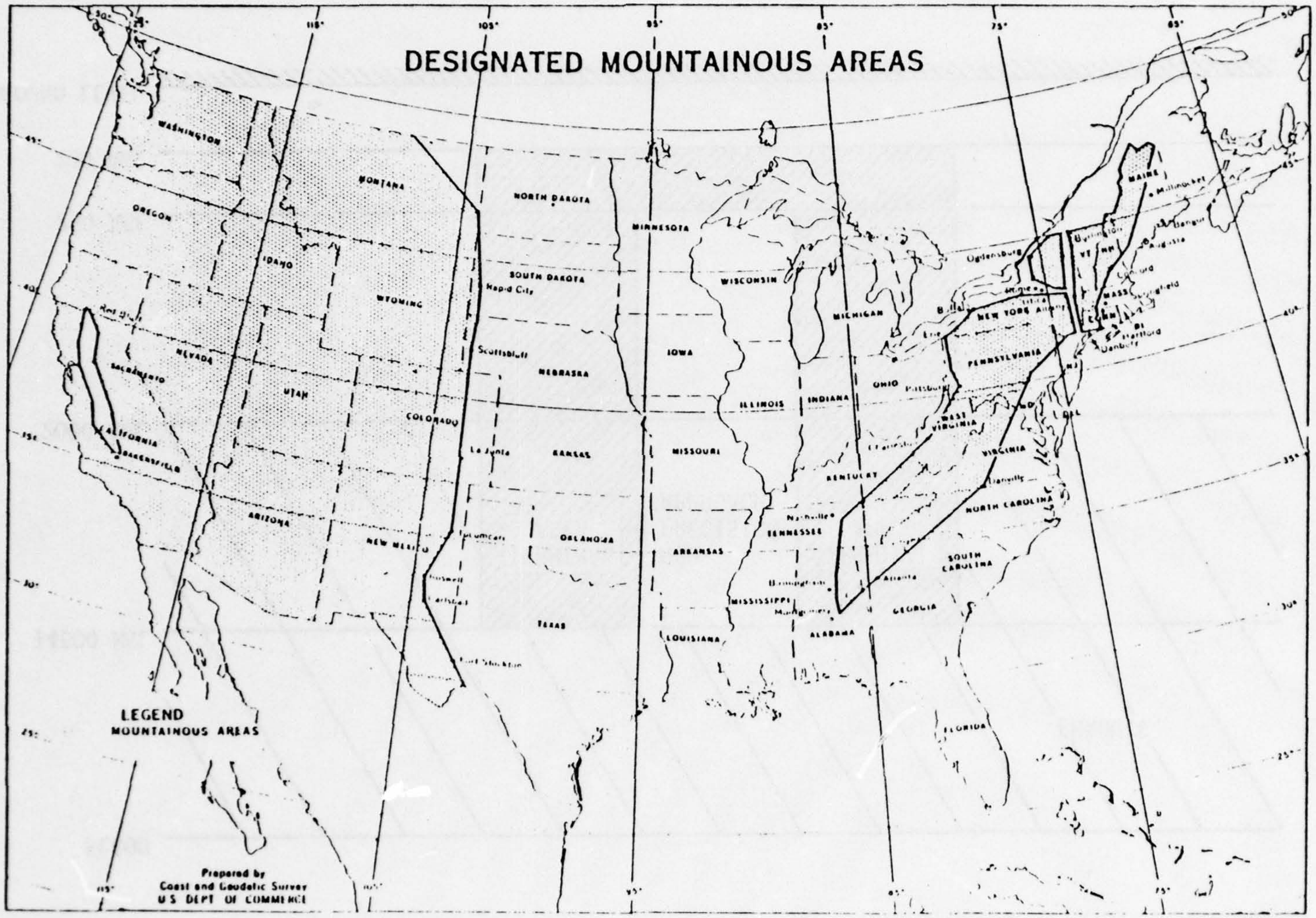


Figure 3.2 CONUS Mountainous and Non-Mountainous Areas

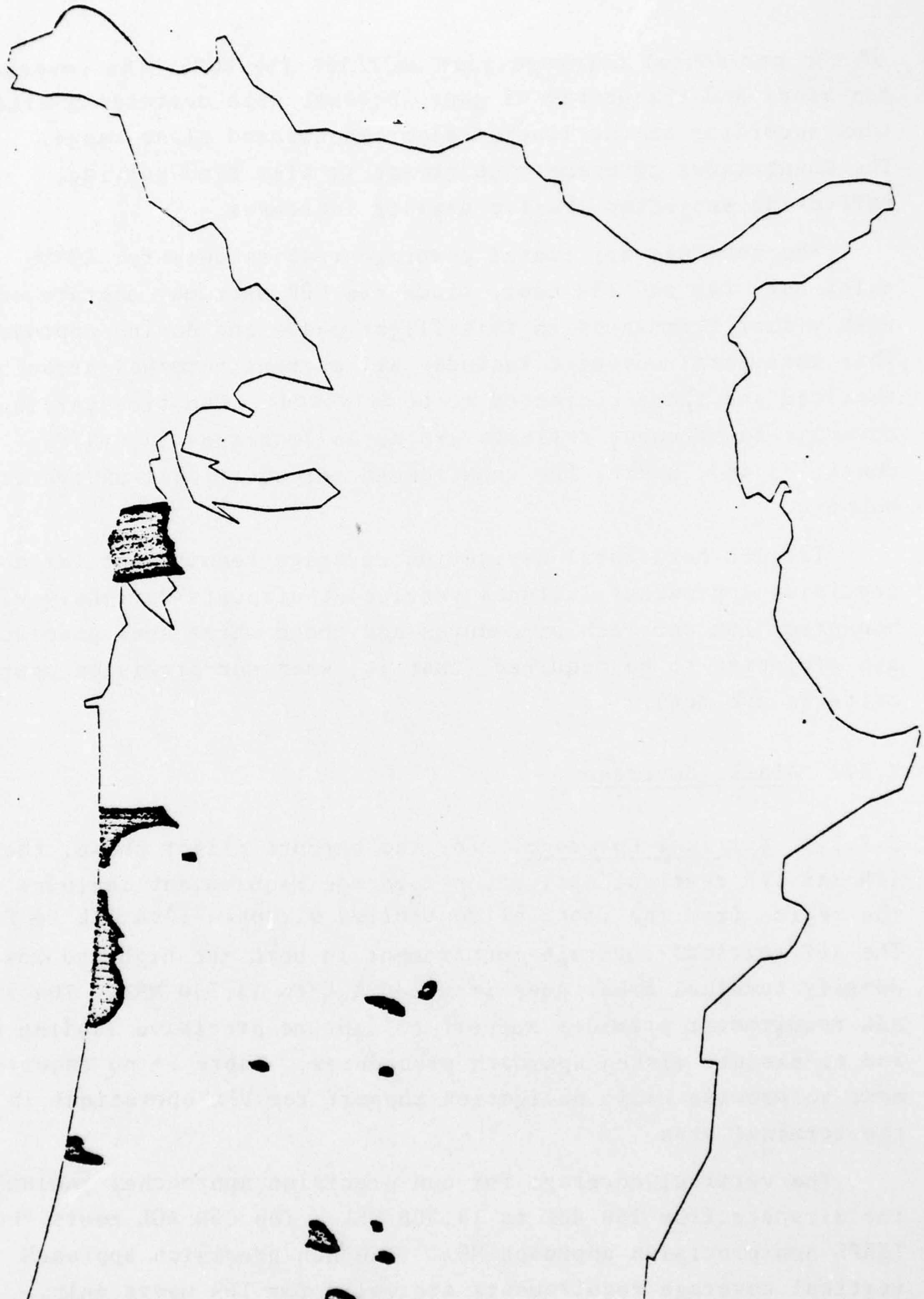


Figure 3.3 VOR Coverage Gaps at FL180

of the horizontal coverage gaps at FL180 for VOR. The coverage gap areas and the number of gaps increase with decreasing altitude according to the line-of-sight restricted slant range. The mountainous coverage requirement is also time-varying, reflecting projected traffic density increases.

The terminal horizontal coverage requirements for CONUS exist only for the IFR user, since the VFR user may operate only with visual references in this flight phase and during approach. This horizontal coverage includes all current terminal areas being serviced and those projected to be serviced. The time-varying coverage requirement reflects projected increases in traffic densities and, hence, the requirement for additional navigation support.

The IFR horizontal navigation coverage requirement for non-precision approaches includes service at airports currently with non-precision approach procedures and those where such procedures are projected to be required (that is, when non-precision approach criteria are met).

3.2.2 Alaska Coverage

3.2.2.1 Vertical Coverage. For the enroute flight phase, the IFR and VFR vertical navigation coverage requirement includes the region from the floor of controlled airspace 1200 AGL to FL600. The IFR vertical coverage requirement in both the high and low density terminal areas goes from 200 AGL to 14,500 MSL. The 200 AGL requirement provides support to capture precision landing aids and to execute missed approach procedures. There is no requirement to provide radio navigation support for VFR operations in the terminal area.

The vertical coverage for non-precision approaches includes the airspace from 250 AGL to 14,500 MSL. The 250 AGL meets the TERPS non-precision approach MDA. The non-precision approach vertical coverage requirements are valid for IFR users only.

3.2.2.2 Horizontal Coverage. The enroute IFR and VFR horizontal coverage requirements are shown on Figure 3.4. The navigation system must provide the necessary radio signals along each of the Victor airways shown in this figure.

The terminal and non-precision approach coverage requirements are also implied in Figure 3.4. At each point where several Victor airways merge or a Victor airway ends, a community normally exists that has a navigation facility. Currently, at each of these communities, the airport has a non-precision approach procedure. Therefore, the candidate systems must provide terminal and non-precision approach coverage at these communities. Depending on community dependence, traffic densities, and other factors, other communities will become candidates as these factors change with time.

3.2.3 Off-Shore Coverage

3.2.3.1 Vertical Coverage. The vertical coverage requirement for off-shore includes the airspace from 500 AGL to 10,000 AGL in the enroute region. This requirement is valid for the IFR and VFR users and pertains to all CONUS off-shore and Alaska off-shore regions. The 500 AGL arises from a 500-feet obstacle clearance requirement. The 10,000 AGL upper bound represents an accepted operational ceiling associated with helicopters.

The terminal area vertical coverage requirement, for IFR users only, extends from 200 AGL to 10,000 AGL. The 200 AGL lower limit provides coverage to capture precision landing aids and to execute missed approach procedures landside. The terminal flight phase upper limit corresponds to the off-shore enroute phase upper limit.

The non-precision approach IFR coverage requirement includes the vertical airspace from 250 AGL to 10,000 AGL. This provides the coverage to meet the TERPS [4] non-precision approach MDA both landside and at sea-based sites. The 10,000 AGL corresponds to the off-shore enroute and terminal upper limit to the vertical coverage requirement.

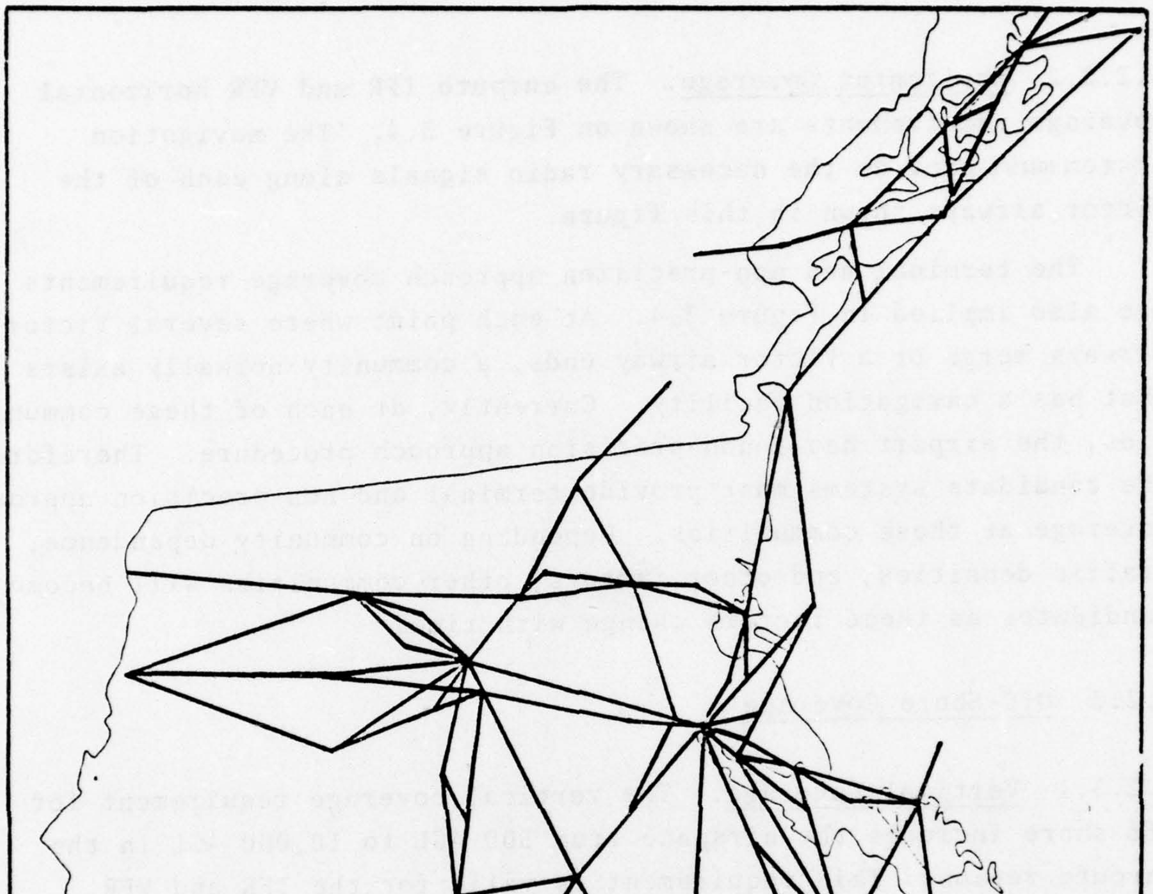


Figure 3.4 Alaska Victor Airway Route Structure

3.2.3.2 Horizontal Coverage. The IFR and VFR enroute horizontal coverage requirements extend to 250 nmi off-shore. Figure 3.5 shows the coverage requirements for the off-shore oil exploration operation. The remainder of CONUS off-shore and Alaska off-shore requires navigation signal coverage to support search and rescue operations. The terminal and non-precision approach IFR horizontal coverage requirements must be adequate to provide navigation support for landside operations adjacent to these specific off-shore regions. Coverage must also be available for operation in the vicinity of sea-based landing sites for which non-precision procedures are required.

3.3 ACCURACY

The accuracy requirement is related to the route width associated with the route structure in the National Airspace System. The accuracy requirement is specified as a route width tolerance which must be achieved a specified percentage of the time. This requirement is the same for CONUS, Alaska, and off-shore.

For both the mountainous and non-mountainous enroute flight regions, the route width is considered to be ± 4 nmi which must be maintained at a 95% level [6 - 9]. In the high density terminal areas the accuracy requirement is more stringent. It is considered to be ± 2 nmi for 2D or 3D navigation [6 , 8 , 10, 11, 12], and $\pm .15$ nmi for 4D navigation [13]. The route width requirement for a low density terminal area is ± 2 nmi in the terminal maneuvering area (within approximately 15 miles of the airport) and ± 4 nmi beyond 15 miles from the airport [6, 8,10, 11,12]. These accuracies must be maintained at a 95% level.

The non-precision approach accuracy requirement is based on the TERPS [4] document which specifies airspace allocations for various navigation systems on final approach. Both precision and non-precision approach procedures are considered in the TERPS. For this study the non-precision approach procedures were examined from which an accuracy value of ± 1.5 nmi about the route centerline was extracted. This is based on factors such as relative location of approach aids to the runway and typical visibility minimums.

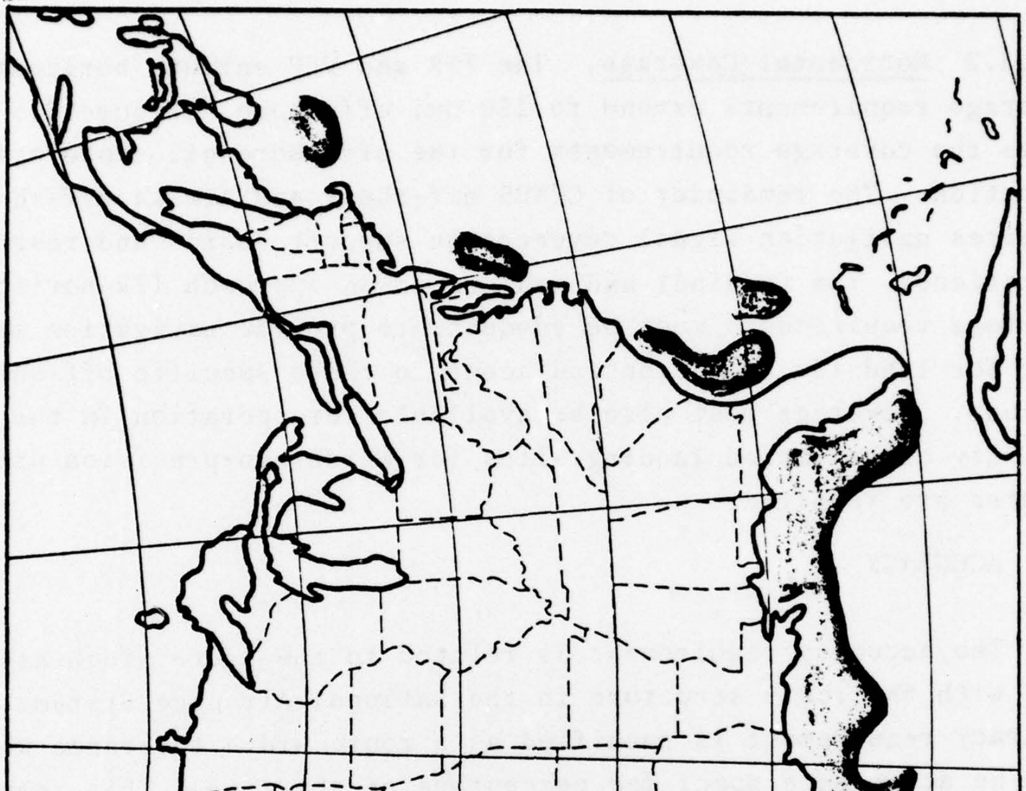


Figure 3.5 Potential Off-Shore Helicopter Operational Areas

3.4 OPERATIONAL CONSIDERATIONS

The operational considerations for CONUS, off-shore and Alaska are identical, hence, no distinction is made in the subsequent discussions with regard to these regions. As indicated previously, the operational considerations are represented by eight requirement categories. These categories relate to the navigation system interface with the other ATC components, namely, communications and surveillance, and to safety factors. The VFR requirements are either identical to or less stringent than the IFR requirement in every category. Hence, the operational requirements are discussed in a generic sense for both the user classes.

3.4.1 Flexibility

This operational category relates to the ability to modify the route structure at will and certify any new routes resulting from this modification in minimum time and cost. This implies that the route structure is independent of the navigation aid location; in other words, waypoints (fixes) and navigation aid locations need not be coincident. Flexibility is not a hard requirement. However, there is a significant cost impact associated with this category in that some candidate navigation systems will be able to meet the desired flexibility with little or no additional costs, whereas others cannot provide flexibility except at a significant cost impact. Therefore, flexibility is retained as a requirement to be used in the subsequent navigation systems evaluation study. This type of flexibility is considered to be required for the enroute, terminal and approach flight phases.

3.4.2 Position Presentation

Position presentation in a format compatible with ATC procedures and charts is a requirement. This category relates to the requirement to present aircraft position in a suitable manner.

Given a charted route structure specified by a connected series of waypoints, or fixes, the aircraft position is to be presented as a deviation off-course. This form of position presentation is valid for essentially all flight phases considered in this study. The only exception is the enroute flight phase where the potential for preplanned direct routing* exists. For preplanned direct only, the position presentation must be chart-plottable and ATC-compatible (for example, range/bearing, latitude/longitude, or LOP). For flight operations above FL240 and for all FAR 121 operators [3], distance along course is required.

3.4.3 Common Input Format [14]

The common input format category is a navigational air traffic control system standardization requirement, in that the avionics must accept course alteration inputs in a format consistent with pilot/controller terminology. Whereas the position presentation category was display of aircraft position to the pilot, this category relates to pilot interface with the airborne avionics. The exact nature of the input format is not specified in this report; however, it is considered that this format should be consistent throughout all flight phases. Examples of input format are latitude and longitude, or range and bearing to a prespecified waypoint [14].

3.4.4 Pilot Workload [15]

The basis for this requirement is that the avionics must be configured so that all course-keeping and course-alteration activities pursuant to nominal flying and ATC intervention can be effectively accomplished. In the enroute region the pilot tasks include aircraft monitoring, communications, and navigation. Enroute profiles are generally sufficiently straightforward that

* Preplanned direct routing is defined as the capability to file a flight plan with an uncharted route between charted or uncharted waypoints and to navigate along this route.

the communication and navigation workloads are minimal. The pilot workload requirement, therefore, is specified as being equivalent to the workload associated with a single waypoint VORTAC-based RNAV system.*

The terminal area route structure and non-precision approach procedures are more complex than the enroute route structure and procedures. Also, the aircraft monitoring task increases as well as the communications task. Therefore, it is necessary that the navigation workload not be so significant as to be the predominant workload factor in the cockpit. Hence, the pilot workload specification for the terminal region and non-precision approaches is specified as being less than or equal to the dual waypoint VORTAC-based RNAV system.*

3.4.5 Failure Alerts

Failure alert is a safety-related requirement. To meet this requirement the avionics must provide failure alert** in the event of signal interruption and avionics failure. This is to account for such factors as signal propagation anomalies, station outages, and avionics failures. The failure alert must be available in all regions so that the pilot is aware of a navigation system failure regardless of where his operations are.

3.4.6 Position Ambiguity Resolution

Position ambiguity implies that a particular navigation system may give an indication of the aircraft position which is not correct. An example of position ambiguity is the potential lane slippage characteristic of the phase-measuring systems or distortion caused

---

* The VORTAC system is used as a basis for this requirement since measures of pilot workload for other systems are not available at this time.

** This is similar to a VOR flag for the current navigation system.

by multipath effects. Because of terrain effects in the mountainous enroute, and terrain and traffic effects in the terminal areas, such position ambiguity must be precluded via system design. Similarly, because of the nature of the flight operations during non-precision approaches, these ambiguities again must be precluded via system design. In the non-mountainous enroute region where terrain effects are minimal and traffic density levels are lower, position ambiguity resolution is less critical. ICAO is promulgating a Minimum Navigation Performance Specification (MNPS) which contains accuracy requirements which will require compliance by all operators in a designated portion of the North Atlantic Airspace referred to as the MNPS airspace. With regard to position resolution ambiguity,

> "... it should also be noted that navigation system performance in the MNPS airspace will be monitored, especially with regard to large deviations. Under this monitoring, operators using navigation systems which permit deviations of 30 nm or more for a total of 1 hour in each 2,000 flight hours, or deviations of between 50 nm and 70 nm (approximately along the adjoining track in 60 nm separation) for a total of 1 hour in each 8,000 flight hours in the system, will be required to take corrective action or be excluded from the airspace." *

Although the MNPS airspace requirements relate to the parallel tracks characteristic of the North Atlantic, it represents an upper bound for the non-mountainous enroute region. Because of higher traffic densities and non-parallel tracks, the requirements will be more stringent. However, a similar analysis will be required to evaluate position resolution ambiguity requirements for the non-mountainous enroute regions in CONUS, Alaska, and Offshore.

3.4.7 System Activation and Position Fix Update Rate

The system activation requirement refers to the time necessary

* Quoted from AC 120-31, "Operational and Airworthiness Approval of Airborne Omega Radio Navigation Systems as a Means of Updating Self-Contained Navigation Systems," dated 12/15/76.

to activate the navigation system from an inactive state or to re-acquire the system following an interruption. Activation encompasses all functions necessary to establish navigation estimates which conform to all the requirements specified in Section III; these functions include signal acquisition, signal lock-on, and system stabilization.

The quantification of the system activation time constraint must consider the maximum period of time loss of navigation information that can be tolerated without seriously impacting safety. For this analysis, it is assumed no other navigation information is available. This acceptable period varies according to flight phase, terrain, and traffic density, as indicated in Table 3.4 and discussed below.

The system activation time constraints were determined in the following manner. Consider the situation when the flight path requires a heading change and the navigation signal is lost prior to commencing the turn. It is now assumed that the aircraft continues to fly straight due to the loss in navigation support. The time that it takes to violate the accuracy requirement is then considered as the system activation time. In other words, a navigation signal must be available prior to violating the route width.

Consider, as an example, the enroute non-mountainous region. It is assumed that route bends will never consist of heading changes in excess of 45°. Hence, an aircraft travelling at 500 knots will penetrate the route width boundary in 0.7 mins. This computation is shown schematically in Figure 3.6. In the non-mountainous enroute region, the traffic density is deemed sufficiently low to accommodate a system activation time range of 0.6 to 1 min. In the mountainous enroute, since terrain poses a constraint, the activation range is limited to 0.3 to 0.5 mins. In the terminal area, course changes can typically be 90°. Aircraft speeds are also reduced in the terminal area. A typical speed of 250 knots was assumed in the computations. The resulting activation times turn out to be 0.5 to 1 min for the

Table 3.4

IFR Navigation Requirements

Time to Re-Acquire

FLIGHT PHASE	REGION	TIME
ENROUTE	NON-MOUNTAINOUS	1-2 MIN
	MOUNTAINOUS	0.5-1 MIN
TERMINAL AREA	LOW DENSITY	0.5-1 MIN
	HIGH DENSITY	0.25-0.5 MIN
NON-PRECISION APPROACH		0.25 MIN

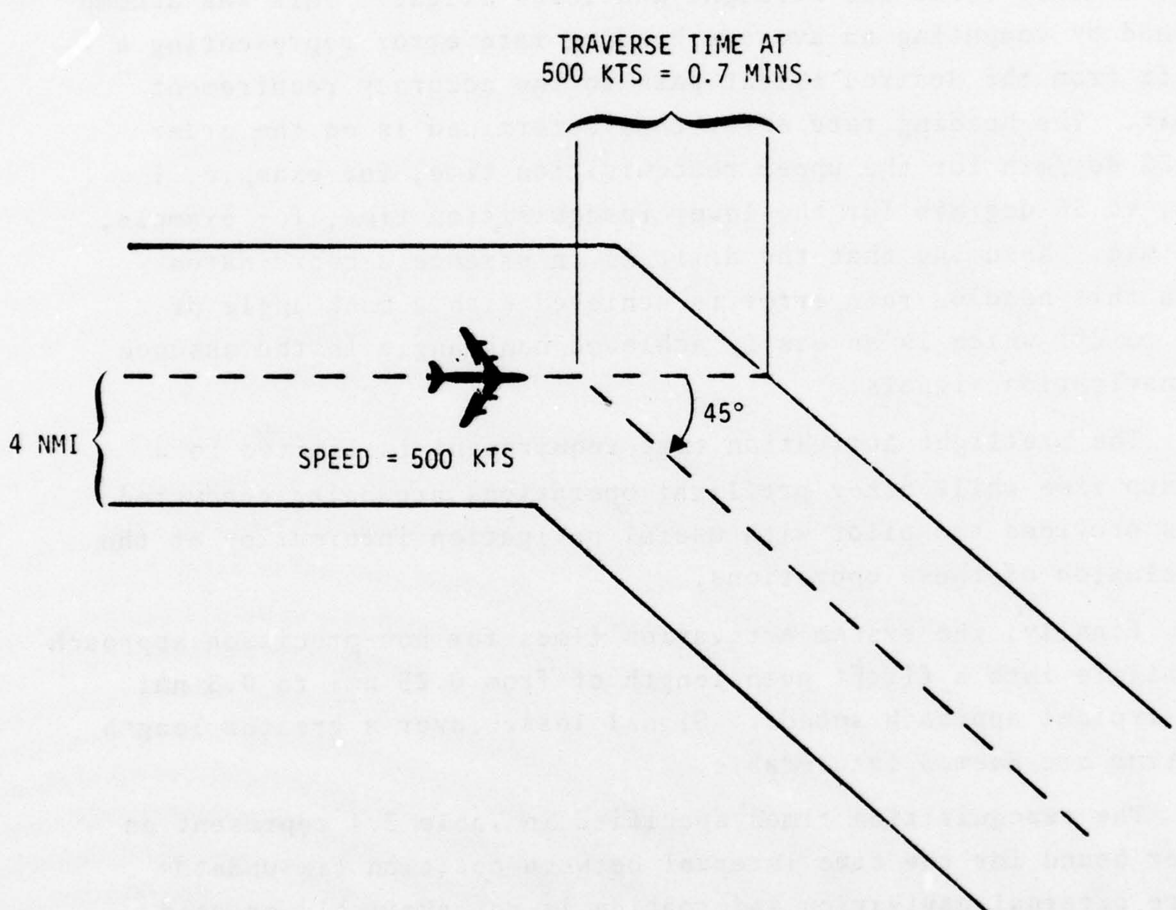


Figure 3.6 Time to Penetrate Route Width Boundary for 45° Route Bend

low density region (±4 nmi accuracy requirement) and an activation time range of 0.25 to 0.5 min for the high density range (±2 nmi accuracy requirement).

Consideration was given to interpret the activation times into a drift error for straight and level flight. This was accomplished by computing an average heading rate error representing a drift from the desired flight path to the accuracy requirement limit. The heading rate error thus determined is on the order of 25 deg/min for the upper reacquisition time, for example, 1 min, to 50 deg/min for the lower reacquisition time, for example, 0.5 min. Assuming that the drift is in essence a coordinated turn this heading rate error is achieved with a bank angle of 10° to 20° which is an easily achieved bank angle in the absence of navigation signals.

The preflight activation time requirement is limited to a warmup time while other preflight operations are being conducted. This provides the pilot with useful navigation information at the conclusion of these operations.

Finally, the system activation times for non-precision approach translate into a flight path length of from 0.25 nmi to 0.5 nmi for typical approach speeds. Signal losses over a greater length of time are deemed intolerable.

The reacquisition times specified in Table 3.4 represent an upper bound for the time interval between position fix updates since external navigation information is not available or used during this interval. For radio navigation systems where information is available only periodically, the lack of signals during specific intervals is anticipated. In contrast, the reacquisition time discussed above relates to unanticipated signal losses. Therefore, for almost all updated navigation systems, dead reckoning capability is provided between the updates. Hence, navigation information is available externally, at the updates,

from the radio navigation aids, and internally, between the updates, from the dead reckoning system. For updated navigation systems without dead reckoning capability, the update interval cannot exceed the reacquisition times specified in Table 3.4. Hybrid navigation systems with updated dead reckoning equipment must meet the accuracy requirements. Therefore, the position fix update interval must be such that the dead reckoning equipment will not cause the aircraft position to exceed these accuracies.

3.5 CAPACITY

The navigation system capacity requirement relates to the ability of a particular navigation system to support all aircraft accessing that system. The capacity requirement is specified as being unlimited. This implies that any navigation system be able to accommodate all aircraft accessing it at all times.

3.6 COMPATIBILITY

Two areas of concern exist for the compatibility requirement. These are compatibility between phases of flight and compatibility with aircraft systems. Simply stated, this requirement is that the navigation system must facilitate safe and smooth transition between all phases of flight. The flight phases include takeoff, enroute, terminal, approach and landing. Furthermore, the avionics must be aircraft-compatible in terms of electrical, physical and RFI (radio-frequency interference) constraints. Systems implemented in Alaska and off-shore should maintain compatibility with the CONUS system with regard to position presentation and input format.

3.7 RELIABILITY

The most important aspect of navigation system reliability is that the system be fail-soft. This means that any failure of one part of the total system will not result in the complete loss of navigation capability. This characteristic can be achieved by redundancy and by system design applied to both the signal source system and the avionics system. The resulting reduced navigation capability after a single failure should be adequate to permit either a safe return to the flight origin or continuation to the desired destination (or to a selected alternate).

The issue of radio navigation system signal reliability requirements is extremely complex. The effort required to quantify the requirement is clearly beyond the scope of this study. At the heart of the issue is traffic separation (safety) and airspace utilization, and the extent to which the radio navigation system contributes to these factors. The issue must be considered within the proper context of the air traffic control (ATC) system. Each of the three elements of the air traffic control system (navigation, surveillance, and communications) bear on the degree of safety provided. In addition, they do so in an interactive manner which varies from situation to situation. Radio navigation system failures have been experienced during which adequate support of safety of flight was provided by surveillance and communications. The immediate effects evident in the event of a primary radio NAVAID failure are traffic delays and increased workload on the part of the air traffic controllers and the cockpit crews. The traffic delays can cause congestion which impacts safety and the increased workload raises the probability of error which also impacts safety. Critical parameters which must be investigated in order to evaluate the severity of the problem caused by a radio NAVAID failure are:

- duration of the failure
- the number of aircraft per sector affected (not the total number of aircraft in the coverage volume)
- weather
- terrain

The accepted procedure followed during a radio NAVAID failure is for the air traffic controllers to assume the navigation function through the use of surveillance and communications. There are, however, some regions within the areas under consideration by this study that are not supported by either surveillance or communications. The most severe of these are those offshore regions which are beyond the range of the ATC surveillance and communications systems. Even here, a worst case approach to establishing the radio navigation system reliability is not straightforward. In the event the radio navigation system is the primary system, backup systems are available. In the simplest case, the aircraft will have as a backup an airspeed indicator and a compass or directional gyro for dead reckoning navigation. In addition, within these regions, communications may be available over a private communications network such as those established by the offshore oil exploration flight operators.

IV. LORAN-C SYSTEM EVALUATION

This section presents an evaluation of the Loran-C navigation system as it relates to the requirements specified in Section III. The section begins with a general description of the system, including a discussion of Loran-C signal propagation and avionics characteristics. Next the Loran-C system performance characteristics are presented as they relate to the following requirements: coverage, accuracy, operational considerations, capacity, compatibility, and reliability/redundancy. The section concludes with a discussion of the capability of Loran-C to serve as a primary navigation system and factors for its implementation.

4.1 LORAN-C NAVIGATION SYSTEM DESCRIPTION

The Loran-C navigation system has been in existence since the early 1950's. Until very recently the operation of the transmitters and the development and use of Loran-C avionics has been driven by military requirements. Its primary user has been the United States Department of Defense and the agency responsible for the transmitter operation has been the United States Coast Guard. As a military navigation system, its availability to civil aviation was limited primarily to a few flight tests or as an add-on feature to some Loran-A receivers which were used for position updates on transoceanic flights using doppler navigators. Because Loran-C was of limited use to aircraft users due to its regulatory restrictions and its limited geographical coverage, it was never seriously considered as a civil aeronautical navigation system.

The visibility of the Loran-C system in the United States took a dramatic change in May of 1974 particularly in regard to non-military users, when the United States Department of Transportation announced that this system would be adopted as the precision navigation system in the Coastal Confluence Zone and could be used for navigation purposes by any interested party: domestic, foreign,

government, commercial or public. In order to achieve full operational status in the coastal areas of the country, the Coast Guard has prepared plans for, and obtained budgetary approval for, six new or reconfigured Loran-C chains for these areas.

The following paragraphs discuss in some detail the characteristics and properties of the Loran-C system which make it capable of being used in the civil aviation environment. In addition, significant operational and technical problem areas associated with Loran-C navigation are considered. A more complete characterization of Loran-C transmission is presented in Reference 17. Those items that are basic to the operation of the system by the aviation community are discussed in the following sections.

4.1.1 Loran-C Geometry

Loran-C is a navigation system which makes use of synchronized low frequency (LF) radio transmissions. The user's receiver system measures the difference in the time-of-arrival of the signals from two pairs of transmitters. Because Loran-C makes use of the time-difference or distance-difference principle, it is often called a hyperbolic navigation system. The two time-difference measurements form two hyperbolas or lines of position (LOPs). The intersection of two LOPs identifies the user's position. A diagram of the Loran-C position fix geometry is shown in Figure 4.1.

A set of Loran-C transmitters with similar signal characteristics is called a chain. Each chain is composed of from three to six transmitting stations. One transmitter is designated the master station and the remaining stations are called secondary stations. In most Loran-C applications the time of the master transmission is used as a reference time. All time differences are measured relative to the time of the master transmission. In most chain configurations the secondary stations are located approximately 400 to 700 nm from the master station. Figure 4.2 shows a typical chain configuration.

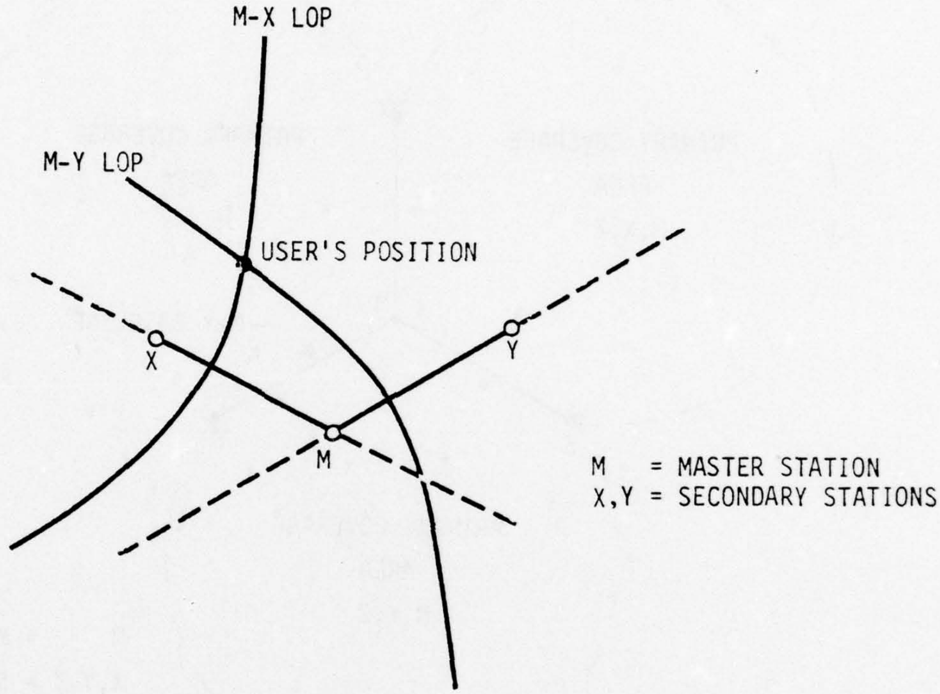


Figure 4.1 Loran-C Position Fix Geometry

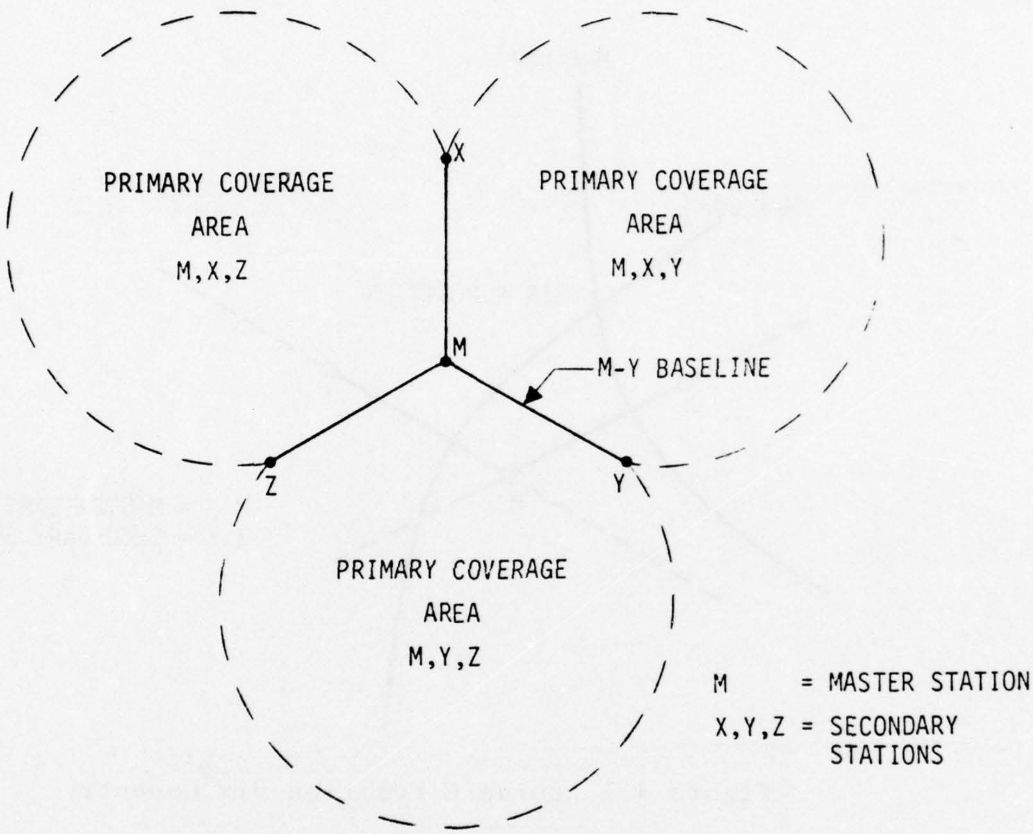


Figure 4.2 Typical Loran-C Chain Configuration

The geodesic*, that connects the master and each secondary station is called the baseline.

4.1.2 Loran-C Signal Characteristics

The Loran-C signal has been designed to overcome some of the inherent difficulties associated with radio navigation systems. The signal has two essential components upon which navigation measurements are made. These components are the pulse and the phase of the LF radio signal. The pulse portion of the signal is of the mathematical form:

$$P(t) = t^2 e^{-\frac{1}{2}(t/65)^2}$$

where t is measured in microseconds. This pulse modulates the 100 kHz carrier. The shape of the pulse is carefully controlled at the transmitter in order to keep the radiated energy in the bandwidth between 90 and 110 kHz, which is the frequency band assigned to Loran-C. The use of the pulse signal in the receiver provides unambiguous time-difference information over the full coverage area of the Loran-C chain. A diagram of the Loran-C pulse is shown in Figure 4.3.

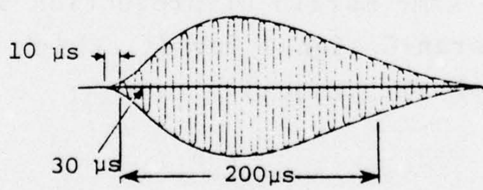


Figure 4.3 Loran-C Pulse

*I.e., the shortest line on the Earth's surface between two points.

In order to obtain a greater degree of accuracy than can be obtained from measuring the leading edge or some composite zero crossing of the pulse, a measurement is made on the phase of the 100 kHz carrier signal. In order to select the proper cycle upon which to measure the phase, the pulse measurement must be accurate to within one half a cycle, or ± 5 μs. Most automatic Loran-C receivers make use of the zero crossing of the third cycle on which to make the phase measurement. This zero crossing occurs at a point 30 μs after the beginning of the pulse. The selection of the 30 μs phase sampling point was based upon a trade off between signal power, which reaches a peak 65 μs after the beginning of the pulse, and skywave contamination. At 100 kHz the Loran-C signals are reflected from the D layer of the ionosphere which is approximately 70 to 90 km in height. The signal that is seen by the receiver is a combination of the groundwave and skywave signals. In reflecting from the ionosphere, the skywave signal travels a greater distance and takes longer to arrive at the receiver than the groundwave signal. Figure 4.4 shows the amount of time that the skywave is typically delayed relative to the groundwave signal. It can be seen that for ranges greater than 800 nm, the skywave can begin to contaminate the groundwave at a point 40 μs beyond the beginning of the pulse. Consequently, measurements made on the phase of the signal prior to 40 μs are unaffected by skywave. The selection of the 30 μs sampling point, then, provides some margin of protection against skywave contamination. The Loran-C signal format, which is pictured in Figure 4.5, consists of the following events:

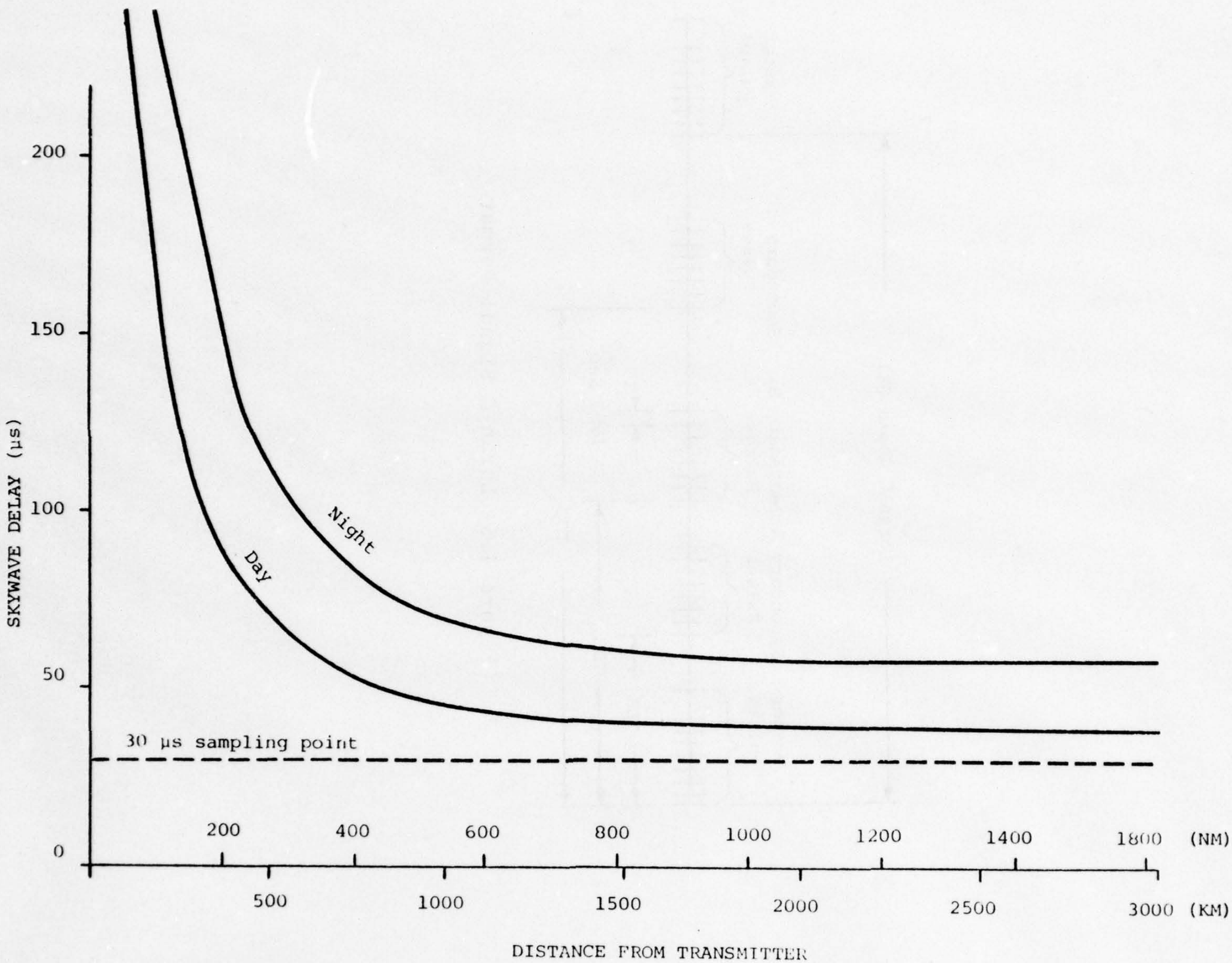


Figure 4.1 First Hop Skywave Delay Relati[illegible]

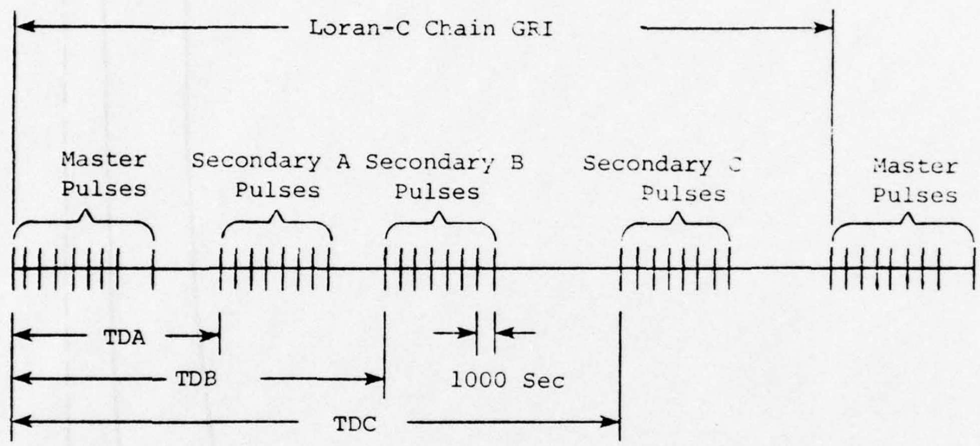


Figure 4.5 Loran-C Signal Format

(1) The master station transmits eight pulses spaced 1000 μs apart and a ninth pulse 2000 μs after the eighth pulse.

(2) The first secondary station transmits eight pulses spaced 1000 μs apart. The first pulse of the secondary station is delayed by a specified amount of time called the coding delay (TDA) from the master's first pulse.

(3) The next secondary station transmits a pulse group identical to the first secondary station but with a greater coding delay (TDB).

(4) Each remaining secondary transmits identical pulse groups but with their own unique coding delay. In most chains the secondaries transmit in alphabetical order. The coding delay for each station is selected such that no two Loran-C groundwave pulses from any stations in the chain overlap in time in any part of the coverage area.

(5) After all of the secondaries have transmitted their pulses, the process is repeated beginning with the master transmissions. The repetition period is called the group repetition interval (GRI). The GRI of each chain is unique and provides a means of discriminating between chains. The GRI may range from 40,000 to 99,990 μs in 10 μs increments. The GRI value of the chain divided by 10 is called the rate of the chain. Permissible chain rates thus vary from 4000 to 9999.

The phase of the 100 kHz carrier may be shifted by 0 or π radians. A zero radian shift is denoted by a (+) sign and a π radian shift is denoted by a (-) sign. The phase code of the master differs from that of the secondary stations, and the phase code of adjacent GRIs are different. The two phase codes of the GRIs are called A and B. The nominal Loran-C phase codes are shown in Table 4.1.

Table 4.1

Loran-C Phase Codes

	Station	
GRI	Master	Secondary
A	+ + - - + - + - +	+ + + + + - - +
B	+ - - + + + + + -	+ - + - + + - -

In order to achieve continuous geographical coverage of Loran-C over large areas, it is often necessary to use two or more chains. In order to reduce the number of transmitter stations required, a station is often made a part of an adjacent chain. When this occurs the station is said to be double-rated. Both masters and secondaries may be double rated; i.e., a transmitter may be a master for one chain and a secondary in the other chain or it may be a secondary for both chains. During the period of time in which the double-rated transmitter would be required to transmit for both chains, the pulses from one chain are suppressed. This procedure is called blanking. Blanking is determined on a priority basis according to the following criteria:

- A master is never blanked
- If operational considerations dictate that the signals from one chain are more significant than from the second chain, then the pulses from the less significant chain are blanked. This situation could arise in the case of one chain being used for primary coverage and the second chain being used for redundant coverage.
- If both chains are equally significant the chain with the lower GRI is blanked.

All transmitters in the Loran-C chain are equipped with cesium frequency standards. This standard is used to control the time of transmission of that transmitter. In addition, pulse shape is controlled by the transmitter station. The phase of the secondary is controlled by monitor receivers at a remote site in the service area. This site is called a Service Area Monitor (SAM). One SAM site may control the phase of one or more secondary transmitters. The SAM site in some chains is located near the master station. The SAM receives and measures the time difference between the master and the appropriate secondary transmission. This received time difference is compared to a control time difference value which has been determined through calibration procedures. Changes in observed time difference values may be caused by oscillator drift and weather phenomena.

4.1.3 Avionic Characteristics

The description of the Loran-C airborne system in the following paragraphs is that of a basic RNAV system with the capability to meet AC90-45A requirements, plus the added parallel offset capability that has been shown to be useful in both enroute and terminal area operations [18, 19]. In addition, the system description includes the Loran-C receiver control and computation capabilities.

4.1.3.1 Antenna System. The antenna systems used with Loran-C systems range from the conventional ADF-sense antennas to complex, three-axis, crossed-loop antennas used on military fighters. The type most useful to civil users are the sense antennas, due to their lower cost and independence from external heading system inputs. At LF frequencies, sense antennas are susceptible to precipitation static problems when the aircraft encounters clouds, precipitation or dust, and the electrical discharges can create noise which in turn can reduce the signal-to-noise ratio to less than acceptable values for reliable navigation. This situation is more severe at high aircraft speeds. The electrical charges can be discharged through the use of static dischargers on the trailing surfaces of the aircraft. The precipitation static problem can be significant in lower cost installations especially in medium and high performance aircraft.

The Loran-C signal level can be as low as a few microvolts in some signal areas. In order to avoid contaminating this low signal with electrical noise from other aircraft systems, an antenna coupler (preamplifier) is used at or close to the antenna location. Any significant separation of the antenna and coupler presents an opportunity for interference to enter the navigation signal.

4.1.3.2 Loran-C Receiver. The front end of the Loran-C receiver spans the 90-110 kHz bandwidth required to receive the Loran-C pulse with a minimum of distortion. The frequency response falls off sharply on lower and higher frequencies to reject out of band interference. Tunable notch filters are used in the front end design to reject any near-band or in-band CW interference. The notch peaks are very sharp to avoid significant distortion of the Loran-C pulse. It is desirable, from a pilot workload standpoint, to have the notch filters be automatically tuned to reject any strong interference signal.

The receiver must be capable of acquiring and tracking the third cycle zero-crossing of the master and two selected secondary stations. Additional stations in the same chain (same GRI) may be tracked if greater capability is desired. After the received pulses have been identified as to the station from which they were transmitted, the receiver may operate in a master-independent mode, which provides greater flexibility in station selection and may increase the coverage area.

All receivers must check for skywave interference. This may be done by sampling prior to the nominal reception time of the pulse and testing for the presence of a signal. If a signal is present, then skywave rather than groundwave has been acquired and the sampling time should be moved ahead to the groundwave pulse.

The dynamic range of the receiver should be sufficient to receive both nearby stations and distant stations. For example, a 4MW transmitter will produce a signal strength of approximately 1 v/m at a distance of 10 nm from the station, while the same receiver may be required to receive a signal of 30 μv/meter or less in northern Alaska where the atmospheric noise is quite low. Consequently, a dynamic range of about 100 db is necessary.

One final requirement for the receiver part of the Loran-C navigation set is the ability to track high performance aircraft around turns, holding patterns, and other typical civilian type

maneuvers without loss of tracking on the cycle measurement. In order to get accurate time-difference measurements, manufacturers often heavily filter the cycle matching process with a phase-locked loop. Sudden changes in time-difference rates can cause the loop to lose lock and perhaps reacquire the wrong cycle, and thus present an incorrect time-difference value. Velocity aiding from the wideband envelope tracking loop or from an external source such as air data or INS can assist the cycle tracking loop and prevent this phenomenon from occurring. Thus the receiver is capable of tracking the Loran-C cycle through all speeds and maneuvers that the aircraft may encounter in normal ATC type operations.

4.1.3.3 <u>Loran-C Coordinate Converter.</u> The Loran-C coordinate converter changes the time-difference information into useful navigation information. A necessary requirement for conversion of time-difference information is the storage of chain constants. These values include station locations, coding delay, baseline lengths and phase-code data for each station in the chain. In order to be useful over the entire CONUS the converter should be capable of storing data from at least six chains. If the set is to be used in Alaska as well, it may be necessary to add data for two additional chains. The chain constants may change from time to time for operational reasons or as new chains or stations are added. Thus it is necessary that the chain constants be modifiable either mechanically or electrically.

The coordinate converter must be able to accept and store at least two RNAV waypoints. Additional waypoint storage capability is a desirable system characteristic. The coordinate system in which the waypoint is entered into the computer can be in latitude/longitude or in time-difference values. Each coordinate system has advantages and disadvantages. The advantage of the latitude/longitude system is its compatibility with existing charting, its familiarity to large segments of the pilot population, and its independence from specific station selection. The disadvantage of this sytem is in additional computer complexity. The need for

additional computer complexity comes from the requirement to accurately model the phase propagation characteristics of the Loran-C signal. Inaccuracies in the modeling process will cause grid bias and grid warpage type errors in the waypoints. These errors may amount to several hundred feet in some parts of the coverage area. These errors may be minimized to some extent by careful selection of speed-of-light values and phase retardation curves in the computer. The use of time-difference or coded time-difference coordinates can all but eliminate grid warpage and grid bias errors. The computed time-difference values in this instance refer to values computed using complex models of the actual propagation paths including conductivity and terrain variations along the path. The disadvantage of using the time-difference coordinates is their lack of familiarity to pilots and the additional cost of measuring or computing the time-difference coordinate values at each charted waypoint. An additional disadvantage is the dependence upon the use of specific stations. The time-difference input must identify the specific station pair corresponding to a particular time-difference value. If these stations are unavailable for any reason and other station combinations are used during the flight, the grid bias and grid warpage factors will not be properly corrected and the system accuracy will degrade.

The coordinate converter also develops RNAV-type signals to drive displays and flight instruments. Among the RNAV signals that must be computed are:

- distance to waypoint
- cross track deviation
- distance between waypoints
- desired track
- direct to waypoint
- parallel offset from parent track

4.1.3.4 <u>Input/Output Characteristics.</u> The input/output characteristics of the Loran-C navigation set are generally similar to other RNAV systems with some additions for controlling the Loran-C receiver. The RNAV inputs include:

- waypoints
- waypoint selection
- parallel offset distance
- magnetic variation (may be stored internally)

Additional Loran-C inputs include:

- chain selection - GRI
- station selection - master, W,X,Y,Z,T secondaries
- notch filter controls (if manual)

Typical RNAV outputs include:

- ability to display all input parameters
- distance to waypoint
- bearing to waypoint
- cross track deviation
- TO/FROM waypoint flag
- appropriate flight control parameters to interface with CDI
- distance to waypoint indicator
- HSI driving signals
- flight director driving signals

The system must also be capable of annunciating problems associated with any portion of the system. Such annunciators include:

- loss of signal
- low quality signal
- poor geometry from selected stations
- loss of aircraft power
- system self-test parameters

4.2 PERFORMANCE CHARACTERISTICS

This section presents a description of Loran-C performance characteristics and an assessment of the degree to which these characteristics meet the system requirements presented in Section III.

4.2.1 Coverage

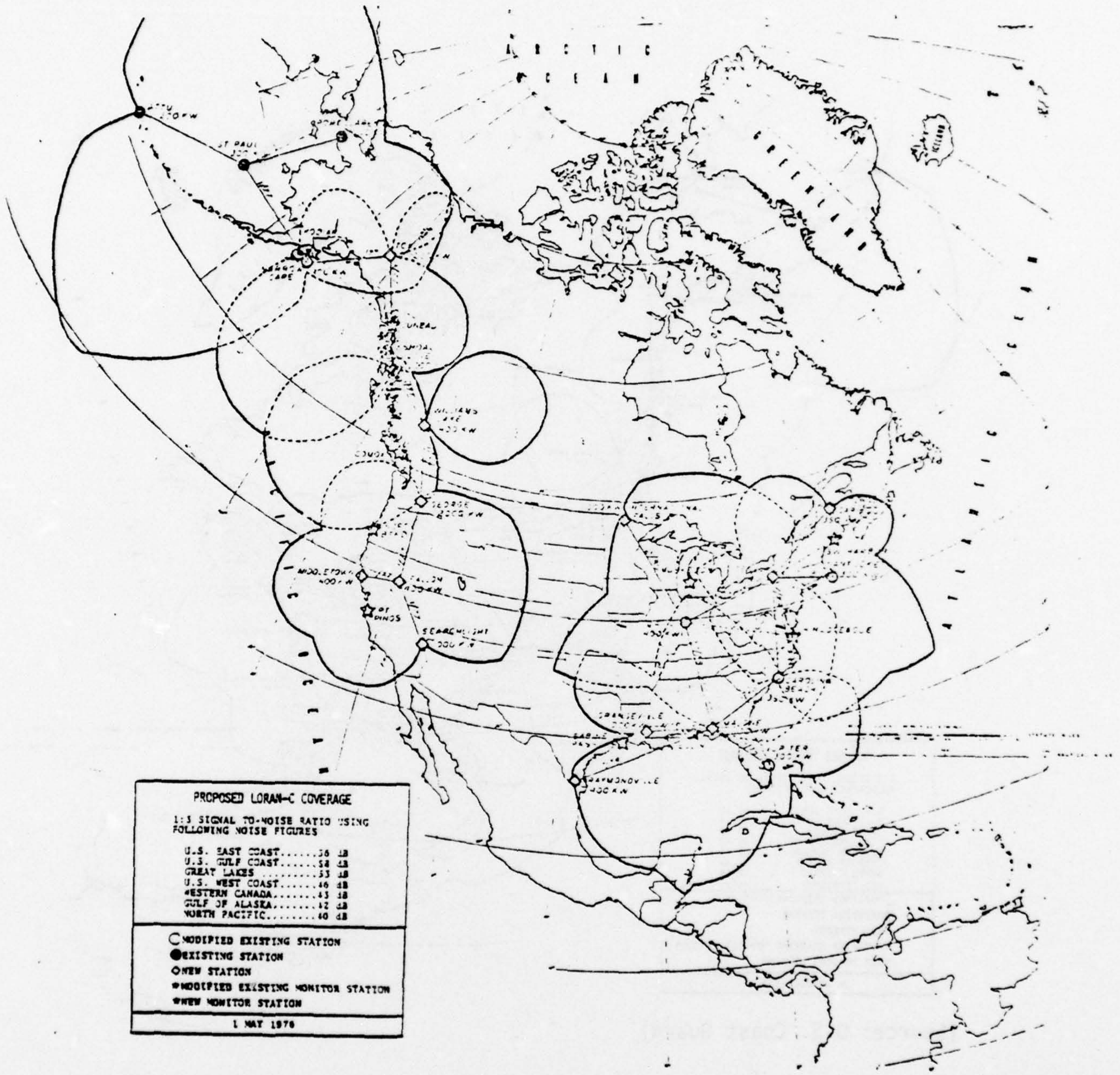
Loran-C coverage charts are computed and published by the United States Coast Guard. The charts illustrate the expected groundwave coverage boundaries as determined by theoretical calculations. The contours are based on signal-to-noise ratios (SNR) greater than 1:3 and geometry such that the 2-drms position error is less than 1500 ft. Measurement error is not included in the coverage

contour charts. The signal-to-noise ratio and the accuracy considerations are discussed in greater detail in Appendix A of Vol. III.

4.2.1.1 CONUS and CONUS Off-shore. A map of the expected Loran-C coverage after the Coastal Confluence Zone (CCZ) transmitters are commissioned is shown in Figure 4.6. The seven chains which are used to provide navigation signals in the CCZ are listed in Appendix A. It is quite evident that the central part of the CONUS area is lacking in Loran-C coverage. In order to complete the CONUS coverage, the Coast Guard has proposed an eighth chain called the Mid-Continent Chain, which is composed of a master station near Springfield, Colorado, two new secondary stations near Harlem, Montana and Terlingua, Texas, and double rating the International Falls, Minnesota, Grangeville, Louisiana, and Searchlight, Nevada stations to the new chain. This proposed configuration is shown in Figure 4.7, and the expanded coverage would include all of the CONUS area (station locations are given in Appendix A, Vol. III). Construction and operating funds for the seven CCZ chains have been approved. However, no construction or operating funds have yet been approved for the Mid-Continent chain.

Coverage is extensive in the CONUS offshore areas, with the proposed CCZ chains, extending to 300 nm or greater except in southern Florida where the coverage drops to less than 50 nmi offshore. The area with coverage extending less than 200 nmi offshore lies in a heavily used air corridor that connects Florida, the Bahamas, Puerto Rico, and other Carribean Islands. The Carribean area is recognized by the Coast Guard as lacking in navigational aids, both marine and air, and is receiving increased attention for potential extension of Loran-C coverage.

An example of the coverage that could be obtained in the Caribbean was obtained by placing a master station on eastern Jamaica, a secondary station at Saint John, Virgin Islands and



(source: U.S. Coast Guard)

Figure 4.6 Proposed Loran-C Coverage with the CCZ Chains

(Source: U.S. Coast Guard)

Figure 4.7 Proposed Loran-C Coverage with the CCZ and Mid-Continent Chains

double rating the station at Jupiter, Florida. The resulting coverage diagram is shown in Figure 4.8. Excellent coverage is available for most of the northern Caribbean area. In particular, the air routes between South Florida, the Bahamas and Puerto Rico are well covered. In order to receive the Jupiter Station at Saint John, and vice versa, the transmitter power would have to be in the vicinity of 1MW. This represents a significant increase in the power of the existing Jupiter transmitter which is rated at 300 kW at the present time. The availability of suitable land areas for locating the transmitters may be a potential problem. The only U.S. island in the area of Jamaica is Navassa Island, which has a land area of about 3 sq. miles. If this island is not suitable for a master station, then agreements would have to be arranged with a foreign government for installing and operating the station.

4.2.1.2 <u>Alaska and Alaska Off-shore.</u> Basic Loran-C coverage in Alaska and Alaska Off-shore is adequate in all areas of the state except for the North Slope region. At least one additional Loran-C transmitter is necessary in order to obtain adequate primary coverage on the North Slope. According to the Coast Guard coverage maps, the northeastern part of the state is covered by the North Pacific Chain. A signal-to-noise ratio analysis for Demarkation Point in northeastern Alaska was performed (see Appendix A, Vol. III). The results indicate that the theoretical coverage from the St. Paul transmitter falls about 60 nm short of Demarkation Point. This analysis indicates that adequate reception of the North Pacific chain is marginal in this area and that additional coverage would be necessary along the entire North Slope. An analysis of the signal-to-noise ratio available at remote points along the North Slope was performed (see Appendix A, Vol. III) and it was shown that the Tok station and the Port Clarence station are able to be received throughout the North Slope area. If an additional transmitter were located at the northeastern tip of the State, near Demarkation Point, and if the Port

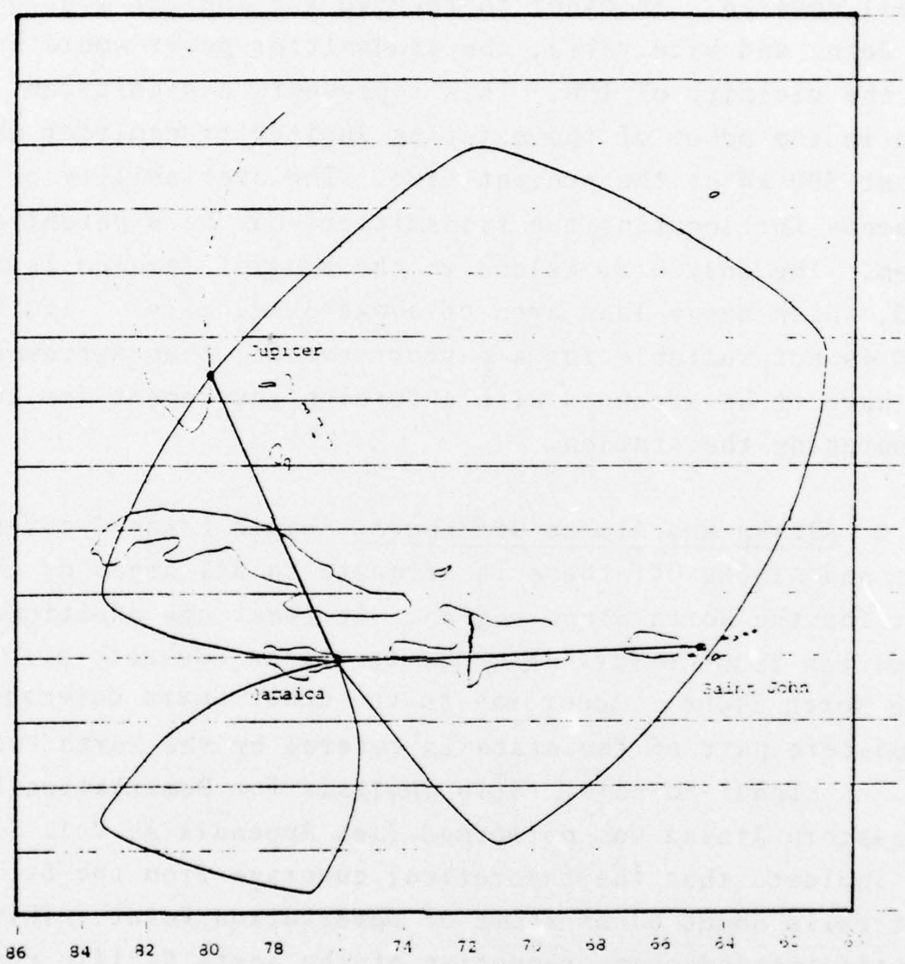


Figure 4.8 Theoretical Coverage Area for the Caribbean Chain
(1500 ft DRMS, 1000 NM Range)

Clarence station were double rated to the Tok master, then Loran-C coverage would be extended to the entire state and all offshore areas out to a distance of at least 150 nm. The coverage diagram of the Tok, Port Clarence and Demarkation Point stations is shown in Figure 4.9.

The CCZ stations along with the addition of three more stations in the mid-continent areas, two stations in the Carribbean and one station in Alaska would essentially complete Loran-C primary coverage for all major U.S. land areas and off-shore areas except Hawaii. A Loran-C user would be within range of one suitable Loran-C triad throughout these areas. An analysis of the adequacy of single coverage is contained in the section relating to Loran-C reliability.

4.2.2 Accuracy

In this section Loran-C accuracy characteristics are discussed in terms of predictability error, repeatability error and relative error. In general terms these error quantities can be described in the following manner as they apply to Loran-C:

(1) Predictability - the accuracy to which a positioning system can find a point for the first time; that is, without knowledge of any bias or warp in the radio field.

(2) Repeatability - the accuracy to which a positioning system can return to the same point in a repeated trial, that is with knowledge of bias and warp in the radio field.

(3) Relative error - the accuracy to which two or more different receivers will indicate the same readings when they are at the same point.

In general, Loran-C systems will encounter some elements of all three types of error in their normal operations.

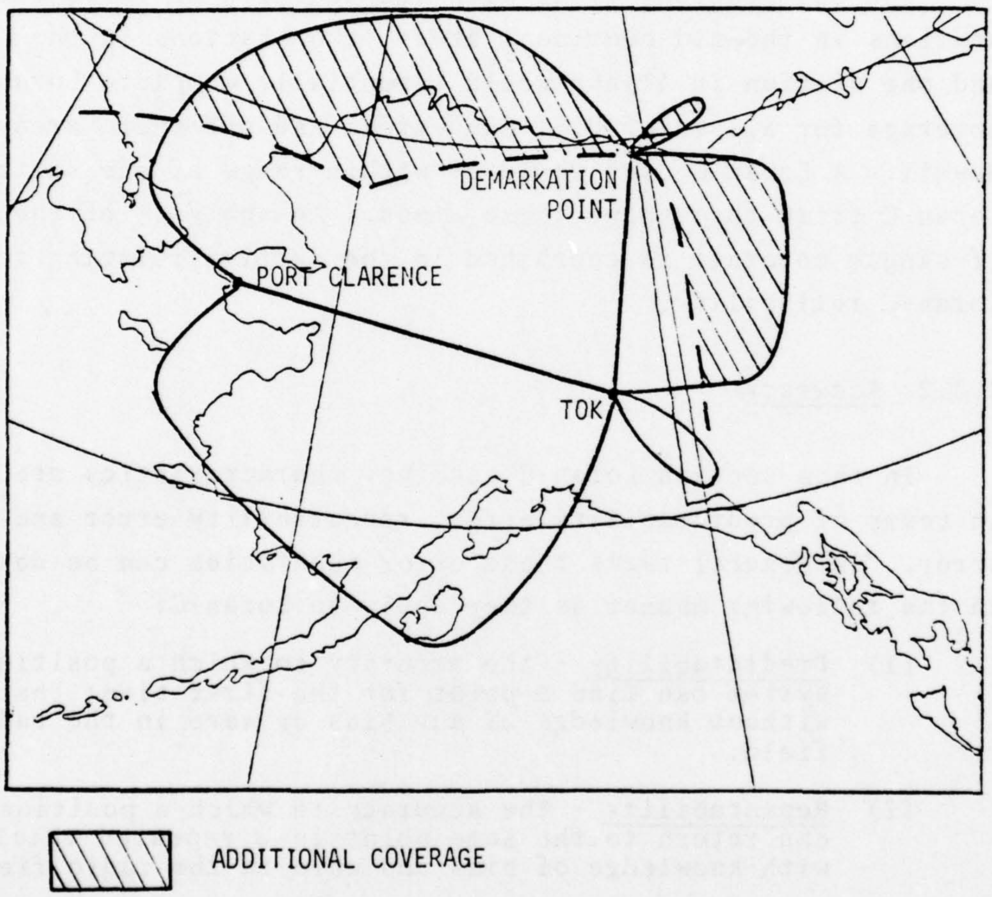


Figure 4.9 Theoretical Coverage for Extended Gulf of Alaska Chain (1500 ft. DRMS, 800 NM range)

4.2.2.1 <u>Predicatability Errors.</u> The major factors that concern predicatability are grid warp and grid bias errors. The grid is formed by applying a mathematical model of the propagation phenomena to points throughout the coverage area, computing the expected time-difference values and plotting them on a chart. When a receiver is then taken to a point and actual time-differences are measured (with zero repeatability and relative error), the difference between the grid value and the actual value is the predictability error. Error components that are constant over relatively large areas (several square miles) are termed "grid bias errors" and components which vary over this same area are called "grid warpage errors." The models of LF propagation used in Loran-C systems generally consist of a speed-of-light term to convert time into distance and a secondary factor correction term which accounts for the phase retardation as a function of distance from the transmitter. Since Loran-C has usually been used over seawater, the speed-of-light and secondary factor terms used in most receivers to date has been representative of seawater propagation. As the signal propagates over land an additional secondary factor, caused by the greater phase retardation over lower conductivity earth, is present. Figure 4.10 shows theoretical values of secondary factor retardation in terms of microseconds of delay as a function of distance from the source. It is apparent that different conductivity conditions will give rise to different phase delays at the same distance from the source.

A theoretical analysis of grid bias error in the Revised East Coast Chain was performed. The navigation receiver was assumed to have been programmed with the seawater phase correction term from Figure 4.10 (σ = 5 mho/meter) while the actual propagation conditions were assumed to be represented by a phase retardation corresponding to the σ = .005 mho/meter curve in Figure 4.10. Obviously this is an oversimplification of the actual propagation conditions in the East Coast area but the model is sufficiently accurate to demonstrate the effect of the additional phase retardation

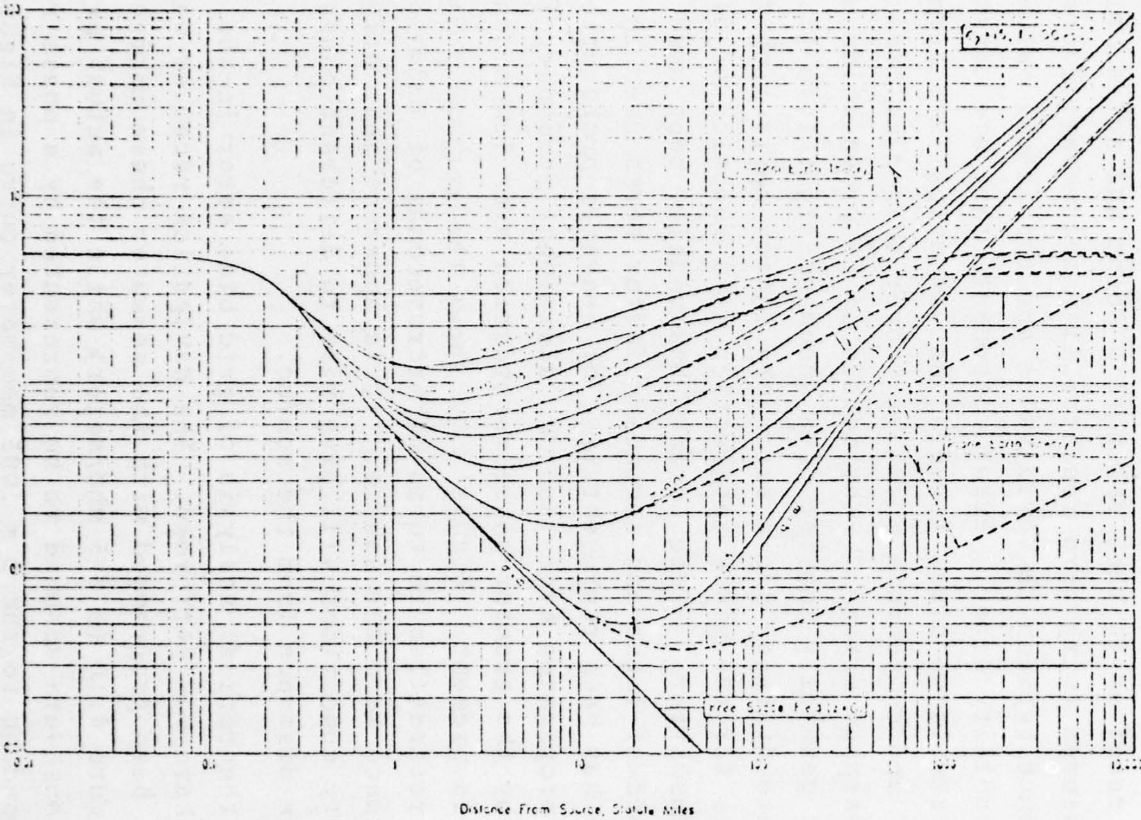


Figure 4.10 Phase of Secondary Factor with Distance from Source for Various Conductivities (Source: Ref. 21)

on the position accuracy. The results of the analysis are presented in Appendix A, Vol. III for various station combinations. It is quite evident from this analysis that the additional secondary factor retardation can cause significant predictability errors in many parts of the coverage area. At the point that is equidistant from all stations, a cancellation of the error occurs because time differences are used. Consequently, in this area errors are small. The major error appears in areas where long distances to one station and short distances to the other stations occur.

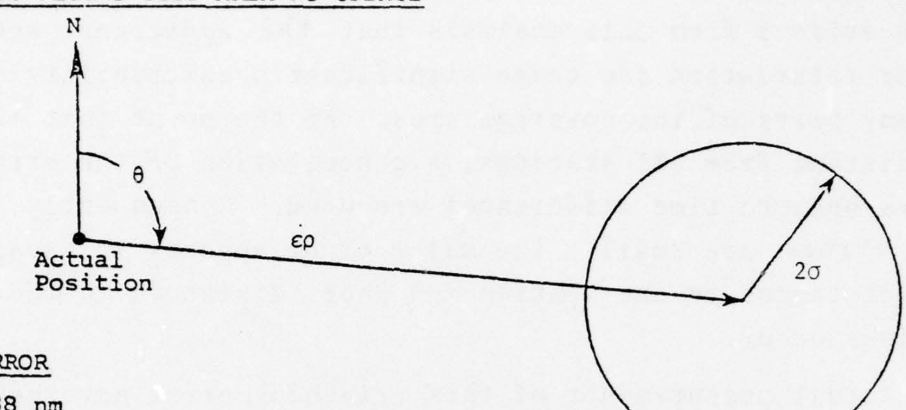
Actual measurements of this grid bias error have been made during a Coast Guard helicopter flight test program in the Cape May, New Jersey area (Reference 22). Airborne position recordings were made throughout the flight test and time correlated with radar measurements taken on the ground. It was found that a bias error of 0.38 nm in an easterly direction was present throughout the flight test, Figure 4.11. The receiver used in the test had the capability of incorporating a position update in the position computation. This update feature was used to try and remove the bias error. Coordinates of the helipad used during the flight test were used as the update point. The helipad was located about 35nm from the flight test area. However, even at this fairly large distance away from the test area approximately 80% of the bias error was removed. Flights using the update procedure showed a bias error of only 0.08 nm. Thus the bias error was quite consistent at the helipad and flight test locations.

Conductivity variations and terrain variations along adjacent propagation paths create grid warpage errors. This problem has been investigated by theoretical studies (References 20,23) and by Loran-C experiments (References 24,25, and 26). The experiments and theory are in general agreement as to the affects of conductivity and terrain induced grid errors. The grid warp problem has been studied extensively at the Eglin Air Force Base in Florida. In Reference 26 a series of tests are described in which a Loran-C

COAST GUARD LORAN-C FLIGHT TEST RESULTS

Scale: 1"=0.1 nm

ACCURACY-FLIGHT TEST AREA-NO UPDATE



MEAN ERROR

$\varepsilon\rho$ = .38 nm
θ = 97° true

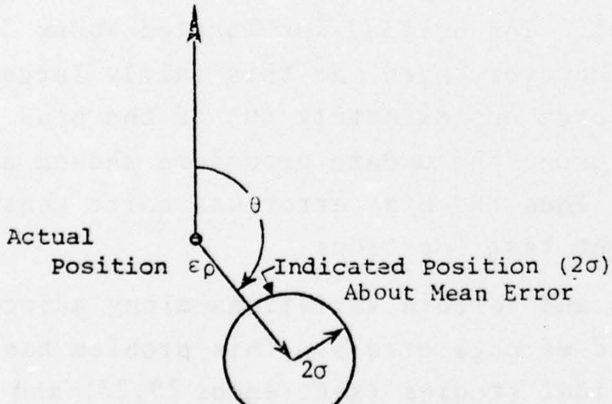
Indicated Position (2σ)
About Mean Error

VARIATION

2σ = .087 nm

ACCURACY - NAFEC AREA - UPDATE AT CAPE MAY TO REMOVE BIAS ERROR

MEAN ERROR	VARIATION
$\varepsilon\rho$ = .084 nm θ = 146°	2σ = .035 nm



FLIGHT TECHNICAL ERROR - ALL FLIGHTS

Approach and Terminal Area	0.01 ±0.15 nm
Enroute	0.00 ±0.12 nm

Figure 4.11 Results of Coast Guard Helicopter Flight Test Using Loran-C Navigation

simulator was used to attempt to match "real world" data. Residual errors for several locations are shown in Appendix A for the Carolina Beach - Jupiter and the Carolina Beach - Dana time differences. Grid warp errors of over 1 μs exist in some areas of the Carolina Beach - Jupiter pair and errors up to 800 μs exist for the Carolina Beach - Dana pair. This data is shown over a 20 by 25 nm grid. One reason for the warpage in the Carolina Beach - Jupiter grid is the abrupt seawater - land boundary in the Florida Panhandle area near Apalachicola Florida. This point of land creates varying land - seawater paths throughout the Eglin area and is considered a major source of the grid warp.

Similar warpage due to coastlines has been shown in the Montauk Point, New Jersey area (Reference 24). The U.S. Army Electronics Command (ECOM) used a manpack receiver mounted in a van to investigate errors in this area. The data from the test were analyzed by least squares contour mapping program and the results are shown in Appendix A, Vol. III. Again peak grid warp errors are on the order of 0.75 to 1.00 μs.

Grid warp can occur from terrain features such as mountains, also. The Army ECOM also studied propagation anomalies in the vicinity of Nittany Mountain near State College, Pennsylvania (Appendix A, Vol. III). Severe grid warp can be observed east of the mountain where errors on the order of 4 to 5 μs can be seen in the TDA grid. These large warpage errors can cause very large position errors in the Loran-C navigation system. These errors could have a definite impact upon final approach minimum using Loran-C in mountains and coastal areas.

4.2.2.2 Repeatability Errors. Errors in repeatability arise from a number of sources. Among those that have been considered are noise sources, aircraft dynamic errors and chain stability errors. The signal-to-noise ratio has been related to position error by several studys including Scott (Reference 27).

In this study, it was shown that filter time constants on the order of 5 to 10 seconds will produce position errors of less than 0.1 μs for signal-to-noise ratios of -10 db.

The use of long filtering times can produce position errors as the aircraft turns or otherwise maneuvers to cause a sudden change in the rate-of-change of a time-difference. The maximum error for such a maneuver is approximately (Appendix A, Vol. III):

$$E_{max} = A\,\tau^2$$

where A = acceleration experienced by the aircraft ($\mu s/s^2$)
τ = post detection filter time constant(s)

A typical acceleration limit used by many civil aircraft is 0.15 g which is .0098 $\mu s/s^2$ along the baseline. The resulting maximum error for a filter time constant of 10 seconds is

$$E_{max} = 0.98\ \mu s$$

This error can be reduced significantly if rate aiding is used to aid the filter in tracking the difference. The selection of an appropriate filter bandwidth is obviously a trade-off between signal-to-noise and dynamic response considerations.

A third source of repeatability error comes from variations in the chain pulse timing. This error source is called chain stability. The USAF measured chain stability at their Eglin Test Facility. Data shown in Figure 4.12 represent corrections that were applied to their data reduction programs in order to correct for chain stability. Mean errors on the order of 0.17 and 0.03 μs were observed and a standard deviation of 0.10 μs for TDA and 0.07 μs for TDB respectively were observed during these tests. During the

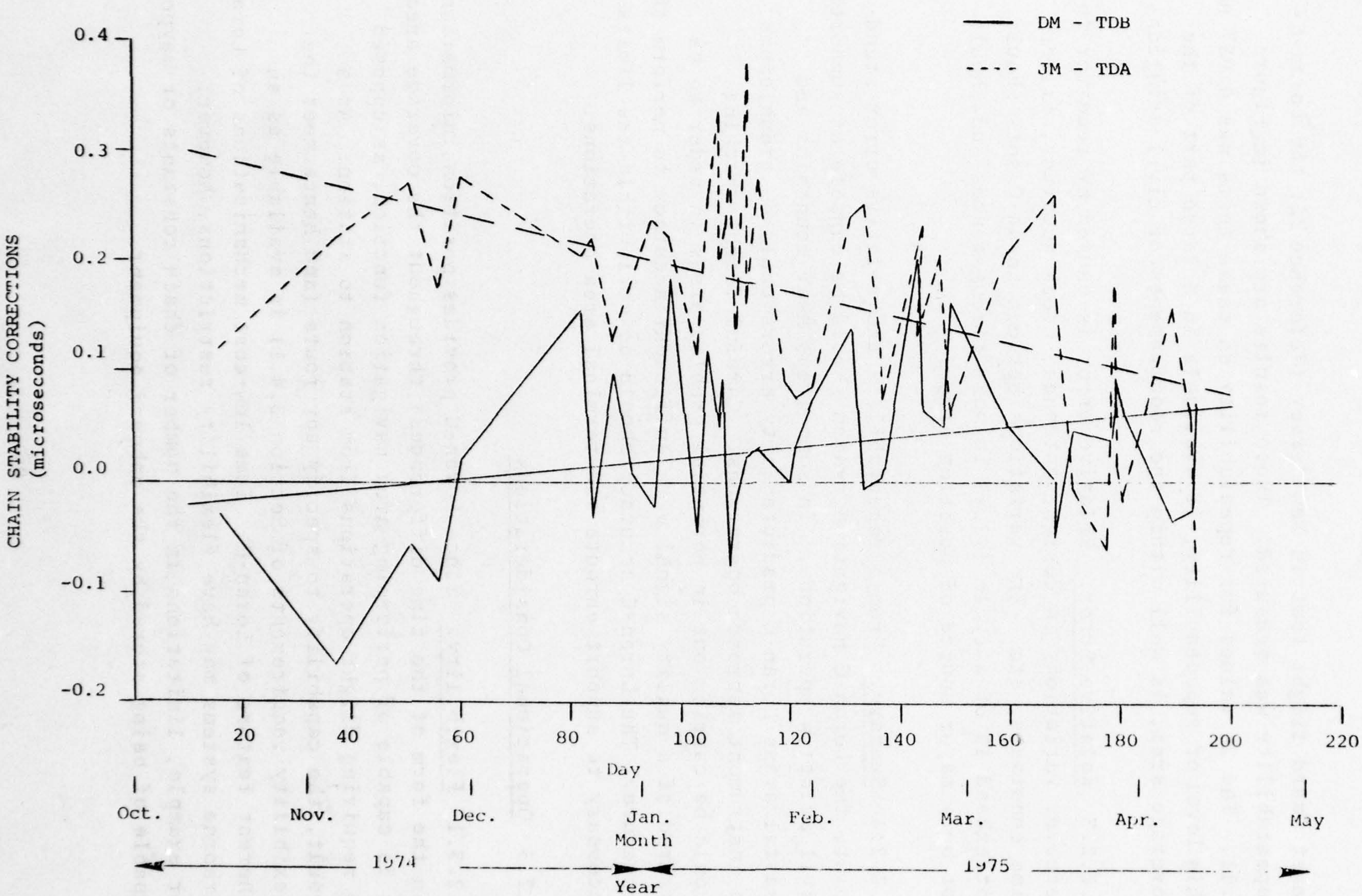


Figure 4.12 Loran-C Chain Stability Corrections Used at Eglin AFB
(Ref.: ADTC-TR-75-54)

Coast Guard flight test in New Jersey (Reference 22) the Loran-C repeatability was measured. These results are shown in Figure 4.11. The 2σ values for repeatability on these tests was 0.087 nm. This level of repeatability, if available in a large part of the coverage area, is well within the requirements of civil aviation.

4.2.2.3 Relative Error. Relative error is caused by receiver-to-receiver variations in design, antennas, clock accuracy, filter time constants, etc. The variations between Loran-C sets should not exceed 1% of a cycle (.1μs) in most circumstances and should not be a major source of position error.

4.2.2.4 Summary. From a repeatability and relative error standpoint, the Loran-C navigation system should be capable of supporting civil aviation operations. In some areas near mountains and coastal areas Loran-C predictability errors could be troublesome in instrument approach operations. Careful flight checking should be carried out in potential problem areas in order to be assured of a quality signal with sufficient accuracy to perform the procedure. The Loran-C accuracy should be well within the limits necessary to support enroute and terminal area operations.

4.2.3 Operational Considerations

4.2.3.1 Flexibility. Since Loran-C provides position information (in the form of the time differences) throughout the coverage area, it is capable of performing area navigation function, as opposed to requiring flight operations from station to station. As a result, the capability to specify any route (and hence meet the flexibility requirements of Section 3.4.1) is available as an inherent feature of Loran-C. Some low-cost mechanizations of Loran-C airborne systems may have flexibility restrictions, however; for example, limitations in the number of chain constants or waypoints capable of being stored by the onboard equipment.

4.2.3.2 Position Presentation. The raw outputs of the Loran-C receiver are time differences from pairs of stations; this information needs additional processing to be useful for navigation. The processing required to convert Loran-C coordinates to position and track-keeping information can be implemented either manually or automatically. Manual implementation has a significant impact on pilot workload and is subject to error. In order to satisfy the intent of the position presentation requirement (Section 3.4.2), automatic processing is required, with associated on-board computational hardware and software.

4.2.3.3 Common Input Format, Pilot Workload and Failure Alerts. These three requirement subcategories relate to the aircraft avionics design. The actual design is dependent upon the individual manufacturers. However, due to the competitive nature of hardware marketing, an attempt will be made by the manufacturers to cause their avionics design to be consistent with the requirements.

4.2.3.4 System Activation and Position Fix Update Rate. Several factors that must be considered in the discussion of system activation relate to the nature of the proposed implementation of the navigation system. If the proposed implementation calls for the navigation system to be utilized as the primary system, then meeting the acquisition time requirement specified in Section 3.4.8 is critical. Implementation of the candidate system in a supplementary role would indicate that meeting the acquisition time criterion is critical only in those regions where the primary system is not suitable and not nearly as critical where the candidate serves as a redundant system to the primary.

Another factor to be considered is the type of avionics that is available. Lower cost avionics may not have an automatic rate-aiding capability. Hence, the acquisition or reacquisition time, while airborne, would have the characteristics of a navigation gap or signal reception loss. Rate-aiding provides a dead reckoning capability during acquisition or during partial signal loss. Also, the avionics could be configured so that during acquisition of a new transmitter the receiver remains locked on to the old transmitter. This again impacts avionics cost.

The Loran-C system shows acquisition times on the order of one (1) to five (5) minutes [22, 29]. This quantity does not meet the requirements specified in Section 3.4.8 for any of the flight regions. As a primary system with low cost avionics the Loran-C system cannot meet the acquisition time requirement. As a supplementary system and/or with more sophisticated and more costly avionics the Loran-C system may be structured so as to meet this requirement. The impact is one of additional avionics cost which is not addressed here.

As discussed in Section 4.1.2, the group repetition interval (GRI) ranges from 40,000 to 99,990 μs and is chain unique. The GRI of a particular chain represents the minimum update interval for the users. Hence, a GRI of 99,990 μs, or approximately 0.1 sec., is within the navigation requirements established in Section III regarding position fix update rates.

4.2.4 Capacity

The Loran-C navigation system is passive in the sense that navigation signals are transmitted from the ground station to the aircraft. Only a single signal is radiated which can be accessed by all aircraft within reception range. Hence, the capacity of the Loran-C navigation system is unlimited, as required (Section 3.5).

4.2.5 Compatibility

The compatibility of Loran-C with existing flight operations has three aspects. The first two aspects concern the compatibility of Loran-C with other navigation instruments and electronic compatibility in the cockpit environment. The third area of compatibility concerns Loran-C and its relationship to international avionic standards.

Since Loran-C is an area navigation system, any properly designed receiver/converter should be capable of being operated in both the present VOR route structure and any future area navigation oriented route structure. The requirements placed upon the airborne system to accomplish this are discussed in Section 4.1.3. In addition, Loran-C can be used effectively to deliver the aircraft to a point from which an instrument approach can be made. Consequently, there should be no difficulty in transitioning between flight phases using Loran-C with other navigation instrumentation such as ILS, MLS, NDB, marker beacons, etc.

The question of electronic compatibility has several potential problem areas but none which seem insolvable from a technical standpoint. Some of the problem areas include precipitation static, acquisition and settle time, wrong cycle selection, low signal-to-noise ratio, cross-rate interference and interference between the ADF and Loran-C when both use the ADF sense antenna. Indeed the solution to problems such as these could affect the cost of the airborne system and reduce the economic attractiveness of such a system. However this situation manifests itself as an economic problem rather than an electronic compatibility problem as long as FAA avionic standards recognize these technical problems and require solution for use in civil aviation.

The question of the compatibility of Loran-C with existing international standards established by the International Civil Aviation Organization (I.C.A.O.) poses a serious problem area for the use of Loran-C as the primary U.S. aeronautical navigation

system. The existing ICAO Standards require the use of the VOR system as the short-distance navigation aid until at least January 1, 1985 (Ref. 30). The possibility of Loran-C replacing VOR as the international standard short-distance aid are very remote since the majority of the areas of the world requiring navigation coverage are not serviced by Loran-C. Consequently, it is quite likely that the VOR system will continue to be the international standard well into the 1980s or even 1990s. This, in turn, will place a requirement upon the FAA to maintain VOR facilities along routes used by international air traffic and to provide air traffic control services to these aircraft. Thus it is unlikely that a major decommissioning of VOR stations could occur even if Loran-C were adopted as a primary national standard.

One plausible scenario for the next 10-15 years, however, has Loran-C being used with increasing frequency as a primary system in remote areas and offshore areas of the CONUS and Alaska with VOR, Omega, VLF, airborne radar or some other suitable aid used as a secondary system in these areas. In the remaining CONUS and Alaskan areas Loran-C could be used as an area navigation system with VOR used as an alternate system in the event of a Loran-C system outage, lack of Loran-C coverage or if for some other unspecified reason a reversion to VOR airways is necessary. In this scenario VOR remains as the primary enroute navigation system in the NAS but Loran-C becomes increasingly important in aviation operations. This scenario assumes that Loran-C is found to be operationally and economically satisfactory to both the FAA and civil users. If this assumption is not fully realized, then the role of Loran-C in civil aviation operations must be appropriately down-graded.

4.2.6 Loran-C Reliability/Redundancy

The reliability of the ground station is one of the most critical issues concerning the use of Loran-C as the primary NAS navigation system. The existing VORTAC system is a widely distributed system with over 1000 stations throughout the nation, each operating independently from the other. The failure of a single station can cause minor disruptions in enroute navigation and perhaps a few missed approaches, but in most areas of the country, an alternate VORTAC is available nearby which can offer substitute enroute service or an instrument approach can be made at a nearby airfield. On the other hand, the Loran-C system consists of approximately 26 stations which are interconnected in eight chains. The outage of a master station can disrupt the operation of the entire chain when master dependent receivers are in use. An example of the impact that a master station outage could have on ATC operations can be appreciated by examining the effect upon the FAA Eastern Region of losing the Seneca Master Station for a one hour period in the middle of the day. The total annual IFR traffic handled forecast for the Eastern Region in the year 1986 is 5,005,000 (Reference 31). This amounts to a daily traffic figure of 13,700 aircraft. If 8% of the aircraft are operating during the peak hour, then 1,100 aircraft will be handled by the Eastern Region during this hour. The absence of a navigation system for this region for this period would place unacceptable levels of workload upon the controllers and the ATC system. For this reason the navigation system must be designed to be at least fail soft if not fail safe to prevent such situations from occuring.

The reliability of the Loran-C system must be analyzed from both the transmitter and receiver standpoint. Statistical data that is relevant to present day transmitters and receivers is some-

what difficult to obtain. The Coast Guard has just finished a major Loran-C Replacement Equipment (LRE) modernization program at several Loran-C transmitter sites [32]. The fact that this LRE program has been in progress has caused reduced reliability statistics due to off-air times for equipment replacement and test. Consequently, the most pertinent data on Loran-C transmitter reliability is available only since the installation of these improvements has been completed. This is a relatively short period of time from which to draw any significant conclusions. However, a one year sample of the East Coast Chain equipment-outage histogram was obtained and some analyses of these data are discussed in subsequent paragraphs.

A similar problem with relevant airborne reliability data exists also. Most airborne Loran-C applications have been oriented toward military programs with high-cost, sophisticated receiver systems. It could be misleading to attempt a correlation between military and civil receiver reliability because the receivers and the operating environment are entirely different. Consequently, in this section, some of the problems that cause reduced reliability in airborne receivers will be discussed in general terms only.

4.2.6.1 <u>Ground Station Reliability.</u> Figure 4.13 is a histogram which presents the number and duration of both scheduled and non-scheduled station off-air times for the entire East Coast Chain for the one year period (December 1975 to November 1976). This time period represents data taken after the Coast Guard LRE program was completed at these stations. The data shown in Figure 4.13 were accumulated and plotted on a probability distribution graph (see Figure 4.14) for exponentially distributed random variables. The exponential distribution is the classical distribution used in relibility analyses. On this graph an exponentially distributed random variable will be represented by a straight line whose slope represents the mean-time-to-restore (MTTR) statistic. Since data were shown in the histogram at one, five and thirty minute intervals, only these values are known for the ordinate values in Figure 4.14.

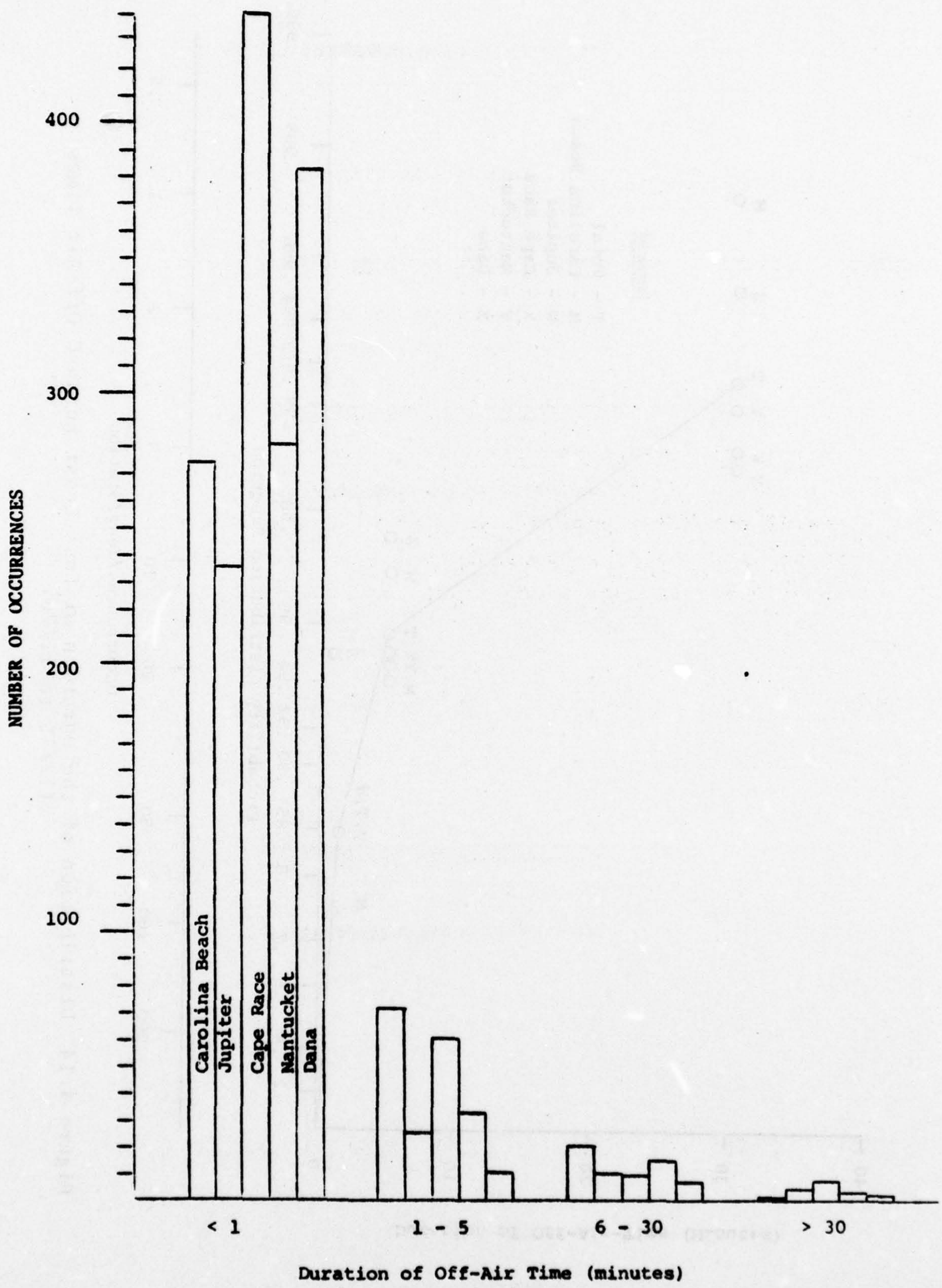


Figure 4.13 Histogram of Loran-C East Coast Chain Off-Air Times

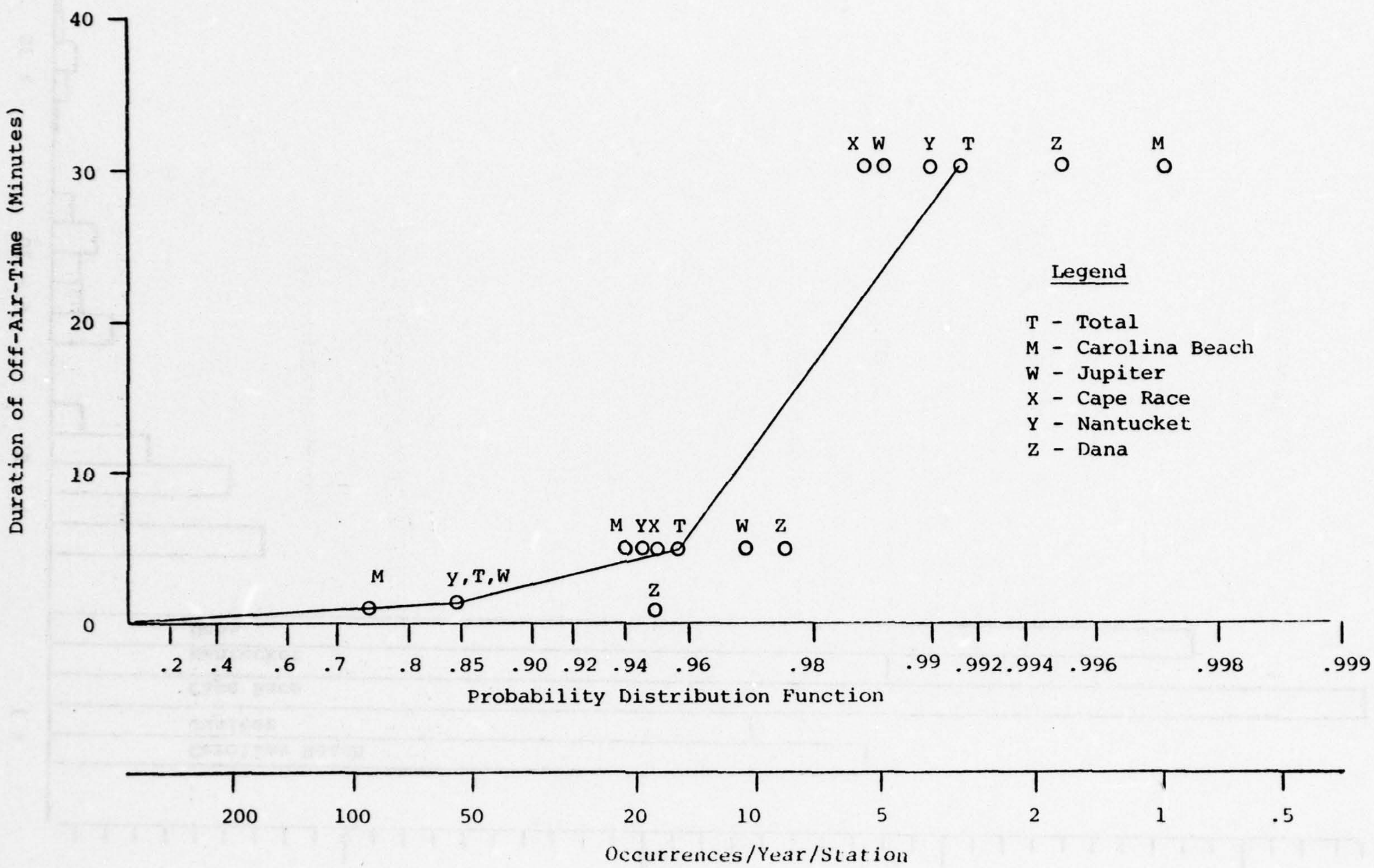


Figure 4.14 Distribution of the Duration of East Coast Loran-C Off-Air Times (12/75 to 11/76)

Data were plotted for each station and the total chain operation. A line connecting the totaled data was drawn which connected the three ordinate values. The data for the one minute and five minute outages form a relatively straight line whose slope represents a mean time to restore of 1.5 minutes. However, when the thirty minute data is added it can be seen that the slope increases rapidly and the mean time to restore statistic increases to about 6.4 minutes at the 30 minute point. This type of distribution pattern could be expected if stations were occasionally turned-off for periodic maintenance. The data shown in the figure also indicates that a station can be expected to be off the air for a period greater than thirty minutes about twice a year. Since three stations are required for navigation, then for six times per year the user may be without a navigation signal for a period of at least 30 minutes if the data in the figure are representative. Of course a one year sample of one chain is not sufficient to provide general conclusions on ground station reliability, but it does indicate possible trends.

The reliability statistics discussed in the preceeding paragraphs are unacceptably high when taken alone. However, if this data represents the reliability of the primary part of a fail-soft type system where an alternate, but possibly, degraded mode of operation is available to the pilot during the station off-air times, then the system may meet the reliability requirements (Section 3.7). The results of this analysis thus indicate that some additional means of navigation must be available to the pilot in the event that one of his three primary Loran-C transmitters should fail. Some of the potential candidates for achieving this requirement are discussed in Section 4.2.6.3 below.

One of the obvious means of increasing Loran-C ground station reliability is through providing redundant coverage throughout the CONUS, offshore and Alaskan areas. This approach was used by a study that was reported in Reference [33]. In this study the locations of the 15 CCZ stations were assumed to be fixed. Additional

stations were added to provide redundant coverage throughout the CONUS region. The analysis was performed for both master dependent receivers and master independent receivers. It was found that 16 additional transmitters would be required for master-dependent receivers and 13 additional transmitters would be required for master-independent receivers. Extending these results to the offshore (including Caribbean) and Alaskan areas was not performed on a coverage diagram basis in the study. However, an extrapolation of the data from the previous study would tend to indicate that about 45 stations would be required for master-dependent receivers and 41 stations would be required for master-independent receievers. Twenty (20) of these stations are part of the CCZ system. The remainder would have to be added for civil aviation purposes. This technique of improving reliability is not without problems. Obviously, the great increase in the number of stations would similarly increase the cost of the system to the FAA. This increase in stations would similarly increase receiver problems caused by cross-chain interference.

4.2.6.2 Airborne System Reliability. The reliability of the airborne system can be affected by a number of factors. Some of the phenomena which create problems with the signal reception and signal processing are described in the following paragraphs.

One of the common problems associated with receiver reliability is low signal-to-noise ratio. The noise may be caused from sources outside or inside the aircraft. Sources of noise outside the aircraft may be atmospheric noise from thunderstorms and other electrical activity in the atmosphere. Sources of noise from within the aircraft can include precipitation static caused by the metal aircraft impacting precipitation or dust particles and developing a static charge. Other sources of noise include aircraft skin currents and other electrical devices operating in the aircraft.

Interference from signal sources which operate in or near the Loran-C band of 90-110 kHz can cause unreliable operation of the Loran-C receiver. In North America the Loran-C band is reserved for navigation and thus the major interference will come from other navigation radio location systems like tactical Loran, Decca, and some of the mini Loran-C chains like St. Mary's River in Canada. The U.S. Navy has a LF communication network that operates on each side of the Loran-C band. In particular, a powerful communication transmitter near Annapolis, Md. operates at 88 kHz and 122 kHz. Interference from CW sources in or near the Loran-C band is usually attenuated in the receiver front-end through the use of notch filters which remove the offending frequencies. The use of these filters will distort the Loran-C pulse slightly. The amount of distortion depends upon the shape of the notch and the frequency of the interference.

A potential major source of interference is Loran-C itself. If all planned chains in North American come into existence, there will be eight (nine with the Caribbean) chains operating in the 90-110 kHz band. Each chain will have its own GRI but there are times when the pulses from different chains will be coincident and cause interference. Careful selection of GRI and, in some cases, phase code can minimize the mutual interference.

One other source of self-interference comes from the Loran-C skywave signal. In some regions of the coverage area, the skywave signal from a remote transmitter may be stronger than the groundwave signal causing the receiver to acquire the skywave. Since the skywave signal is delayed some 400 μs or more than the groundwave, the indicated position will be in error by a considerable amount (5-50 nm). In order to protect the navigation system from obtaining skywave information, receiver systems continue to search ahead of the received pulse for a groundwave pulse.

Generally, through careful design and installation the problem discussed herein can be minimized or eliminated. However, thorough equipment tests and inspection of these problem areas should be accomplished before equipment is approved for IFR operations.

4.2.6.3 Alternate Modes of Operation. The standard operating mode of Loran-C has been through the use of the master and two secondary stations all operating at the same GRI. This mode of operation provides the type of coverage patterns that are shown in Section 4.2.1. However, other modes of operation are possible and perhaps desirable in many instances.

The first and most easily accomplished alternate mode is the master-independent receiver. Once the pulse groups in the GRI have been identified as to their station of origin, they may be tracked independently. Time-difference measurements may be made between secondary stations as well as the master and secondary stations. The use of secondary-secondary time-differences permits the use of other geometry configurations for the position computation and thus may improve the GDOP factors relative to the master-secondary configuration. Another and perhaps more valuable attribute of the master-independent receiver is that the chain operation is no longer dependent upon receiving the master station. Should the master go off-the-air or out of range, then as long as three stations in the chain are being received and the GDOP is satisfactory, position computation and navigation can continue.

Another and more sophisticated type of receiver design is represented by the cross-chain receiver. The cross-chain receiver is capable of acquiring and tracking stations in at least two different chains, each having their own GRI. One time-difference measurement is made using two stations in one chain and the second time-difference is made using two stations in a second chain. Position and navigation computations are made using the chain constants and station locations of the received stations. Coverage patterns for the CONUS, offshore and Alaska could be altered considerably if cross-chain operation were used. The major disadvantage of this type of receiver are increased cost due to the additional complexities associated with the reception and tracking of two different GRIs.

Another alternate mode of operation is the rho-rho mode where time is measured relative to the receiver time standard. Time-differences can be measured by subtracting the time-of-arrival of the pulses if desired. Once position is known, the range to each of the stations is known and the time that the pulse was transmitted can be computed. Through this technique the receiver clock can be synchronized to the Loran-C transmitter clocks, and the drift rate and the bias of the clock can be measured. Should only two stations be available to the receiver, position and navigation computations can continue, but the clock cannot be updated. If a suitable airborne clock is used, then accurate navigation may continue for some period of time without the position error growing too large. Should the additional stations become available, the clock may be synchronized again. The major disadvantage with this system is generally the higher cost of the clock and associated receiver complexity.

One other mode of operation that could provide fail-soft reliability to the Loran-C system is the use of the skywave signal. If position is approximately known, then skywave correction values can be determined and the time-difference can be computed through the use of these corrections. The navigation information will certainly be less accurate than with groundwave Loran-C but accuracy on the order of 2-3 nm can be expected in areas of good skywave signals. If such a system is used, receivers should be capable of informing the pilot that skywave is in use and pilots should be trained to expect less accurate performance with the skywave signals. The receivers must be capable of automatically correcting for the skywave to minimize pilot workload.

4.3 LORAN-C IN THE NATIONAL AIRSPACE SYSTEM

4.3.1 Implementation Factors

The use of Loran-C in the NAS can be accommodated in at least two different manners. First, it can be used as a supplement in areas of VORTAC coverage voids and to provide area navigation capabilities in areas of Loran-C coverage. The other aspect of Loran-C utilization is its use as the primary enroute navigation in the NAS as discussed in the previous section. For use as a supplementary system Loran-C equipment needs to be certified under Advisory Circular 90-45A and suitable operating procedures need to be developed. These operating procedures will vary depending whether the aircraft is being operated under Part 91, 121 or 135 of the Federal Air Regulations. In general, these procedures will consider the areas in which the equipment can be operated, the requirement for additional navigation equipment and the flight phases and minimums to which the equipment can be operated. Although considerable work must be accomplished before Loran-C can be used as a supplementary navigation system, the procedures are relatively straight forward and they have been applied to other systems.

The use of Loran-C as the primary navigation system in the NAS has a considerably greater impact upon many aspects of civil aviation. The problems vary all the way from defining the basic ground station and airborne requirements to adhering to international agreements relative to air navigation facilities. Several of these implementation factors are listed in the following paragraphs.

One of the first tasks in adopting Loran-C as the new NAS navigation system is the development of an implementation plan. This plan would serve as the basic management tool for the adoption of the new system and would contain milestones that must be accomplished, schedules which should be kept and interrelationships between the various aspects of the program. Some of the major milestone activities and nominal periods of concern are as follows:

- System concept definition (1977-1980)
- Cost benefit evaluation (1978-1981)
- Ground station installation (1977-1985)
  - location planning
  - site acquisition
  - site preparation
  - station construction
  - station calibration
  - operational status
  - maintenance standards development
- Airborne equipment definition (1978-1985)
  - redefinition of airways and approach procedures
  - development of TERPs
- Airway facility standards development (1980-1985)
  - monitor station requirements
  - flight checking requirements
- Government agency coordination (1977-1985)
  - Coast Guard
  - Military
  - Federal Communication Commission
  - National Ocean Survey (charts)
- Foreign government coordination (1982-1985)
  - ICAO
  - Canada
  - Mexico
  - West Indies
- Dual system operation (1985-2000)
  - ICAO requirements
  - user transition requirements
  - decommissioning of VORTACs

Very little if any work can proceed without first developing the basic system concept definition. There are several tradeoffs that can be made between ground station coverage and airborne equipment modes of operation. Decisions such as the requirement for master indepedent operation, rho-rho operation, skywave operation, etc., must be made before the ground station requirements can be completely defined. Decisions such as these will impact many other aspects of the implementation problem.

4.3.2 Loran-C as the Primary Navigation System

When comparing navigation requirements for civil aviation applications and Loran-C capabilities, several areas of concern arise. Major areas of concern involve system reliability and

compatibility. The questions involving Loran-C reliability are not so much one of the ability of the station operators to provide reliable, high quality navigation signals but rather a question of the FAA's management philosophy concerning navigation facilities. Questions involving compatibility involve both domestic and international air navigation.

At the present time there are approximately 1000 VORTAC stations in the CONUS each operating independently. At most, two stations are required at any one time for navigation purposes (to determine a fix) and any problem associated with signal availability is confined to the area around the VORTAC. This area is approximately 5,000 sq. miles for a low altitude facility and 80,000 sq. miles for a high altitude facility. A Loran-C master station may serve an area of 1.5 million sq. miles or greater which represents roughly 20 times the area of a high altitude VORTAC and 300 times the area of a low altitude facility. If Loran-C were the primary navigation system, station outages could affect areas of the country that are a sizeable fraction of the CONUS area rather than keep them confined as does the VORTAC system. Widespread navigation system outages could have potentially hazardous impacts upon ATC system safety.

One other navigation facility management philosophy that is appropriate to the question of Loran-C as the primary navigation system is the question of the major purpose of the navigation system. The VOR system is operated by the FAA for the express purpose of providing navigation service to civil aviation. The purpose of the CCZ Loran-C stations on the other hand is to provide navigation services to maritime interests. To the extent that the maritime and aviation requirements overlap, the operating and maintenance procedures of the Loran-C stations could remain essentially the same. However the use of Loran-C for primary civil aviation purposes could impose new and/or additional requirements upon the Loran-C Station operation. Some of the areas which

could be affected are monitor station requirements, phase adjustment procedures, in-service maintenance, outage reporting procedures, chain calibration, auxilliary power requirements, fail safe-fail soft station design and operation, etc. No doubt many operating problems may become evident only after significant experience in the use of Loran-C for aviation purposes has been obtained. Thus the full extent of the dual maritime-aviation operation cannot as yet be determined.

Another problem facing the adoption of Loran-C as the primary navigation system at some future time is lack of operational experience with Loran-C in the National Airspace System. To date no Loran-C system has been certificated for use in domestic airspace although at least one manufacturer is considering applying for certification. Airborne Loran-C experience has been obtained through expensive, complex military systems or special purpose receivers used by the Coast Guard. Additional operational experience is necessary in all phases of civil aviation from general aviation through air carrier operations in order to fully appreciate all operational problems that could beset an untried navigation system. In particular, potential problem areas exist relating to the capabilities of low cost navigation receivers, actual as opposed to theoretical Loran-C coverage, ground station reliability, airborne system reliability especially in low signal-to-noise ratio areas and in precipitation static conditions, grid bias and grid warp errors, etc. Operational experience in many types of aircraft and in many operational situations is necessary before the system can be seriously considered as the primary means of operating in the NAS.

One other problem area associated with the adoption of Loran-C as the U.S. air navigation system is the loss of compatibility with the international standard VOR/DME system. The adoption of Loran-C as an international standard has a very low probability since it is unavailable in many countries that recognize the I.C.A.O. standards. Consequently, the U.S. would be faced with the

alternative of either supporting Loran-C for domestic use and VOR/DME for international operations or operating in the unilateral mode of requiring international operators to adopt the U.S. system and thus rebuff the I.C.A.O. standards.

In summary, the Loran-C system has many attractive technical features to recommend it for use in air navigation. However, its adoption as the primary navigation system for the CONUS, Offshore and Alaskan areas cannot be supported at this time for reasons of lack of operational experience and international incompatibility. In addition, the centralization of navigation responsibility at a few ground station sites could cause major problems in air traffic control during times of station outage.

4.3.3 Loran-C As a Supplemental Navigation System

In terms of a supplemental navigation system, Loran-C should be very capable of CONUS, Offshore and Alaskan areas provided additional ground station coverage is provided in the mid-continent, Caribbean and Alaskan North Slope areas. Most of the objections to Loran-C as a primary system disappear when the system is put in a supplemental navigation role. As long as an alternate mode of navigation is available should a Loran-C ground station fail, then the reliability problem is greatly diminished in importance. In addition as a supplemental navigation system, it no longer would be a problem with regard to maintaining the international standard VOR/DME system.

The one area that remains troublesome however, is the lack of experience relating to civil aviation operations. Experience will undoubtably accompany the expanded availability of the system as the CCZ transmitting stations become operational and manufacturers develop receivers specifically designed for the civil users. Loran-C used in a supplemental navigation role should provide an opportunity to obtain this experience with minimum risk to both the FAA and the system users.

Specifically the major advantages to be gained with Loran-C as a supplemental navigation system relative to the existing VOR/DME system are:

- Full coverage from ground level to all flight altitudes in all areas of CONUS, Offshore and Alaska provided expanded coverage is available in the mid-continent areas (five stations), Caribbean areas (two stations) and Alaskan areas (one station).

- High repeatable accuracy (less than 1/4 nm) throughout the primary coverage areas of the system

- Area navigation (RNAV) capability throughout the entire coverage area of the Loran-C system

The major disadvantages of using Loran-C as a supplemental navigation include:

- Additional cost of developing procedures and facilities for using Loran-C in NAS

- Potential problem areas with precipitation static, system reliability, grid bias and warpage errors, etc.

- Unknown capabilities of civil use Loran-C receivers

In summary, the potential benefits of Loran-C in all areas of CONUS, Offshore and Alaska appear to far outweigh the disadvantages which are largely due to inexperience at the present time. The potential utility of the Loran-C system in the NAS is high. Whether this potential can be realized may only be determined through experience gained in the operational environment.

V. OMEGA SYSTEM EVALUATION

This section presents an evaluation of the Omega navigation system as it relates to the requirements specified in Section III. The section begins with a general system description, including a discussion of Omega signal propagation characteristics and anomalies. Next, the system performance characteristics are presented as they relate to the following requirements: coverage, accuracy, operational considerations, capacity, compatability, and reliability/redundancy. The section concludes with a discussion of the role of Omega in the National Airspace System and factors for its implementation.

5.1 SYSTEM DESCRIPTION

The Omega navigation system operates at VLF in the frequency range 10.2 to 13.6 kHz; world-wide coverage is provided by eight stations A to H shown in Figure 5.1. Trinidad is not shown since it is a temporary station. Each station transmits four frequencies, 10.2, 11.05, 11-1/3, and 13.6 kHz in the time sequence shown in Figure 5.2. The complete cycle for the eight stations takes 10 seconds. In addition, each station will transmit on a unique frequency. Hawaii and North Dakota are already transmitting their unique frequencies of 11.8 and 13.1 kHz, respectively. The segments of the time sequence bear the same letter designation as the station which transmits 10.2 kHz in that segment. This system design requires accurate clock installation only at the transmitters.

The receiver identifies the broadcast from each station and compares the phases of the received signals. The signal identification can be accomplished by equipping the receiver with a commutator which, when properly set initially, can identify the unique time-shared pattern of the Omega transmissions. Because the broadcast from a particular station occurs in the same time slot every ten seconds, the receiver is able to make the identification. The relative phase measurement is performed by comparing

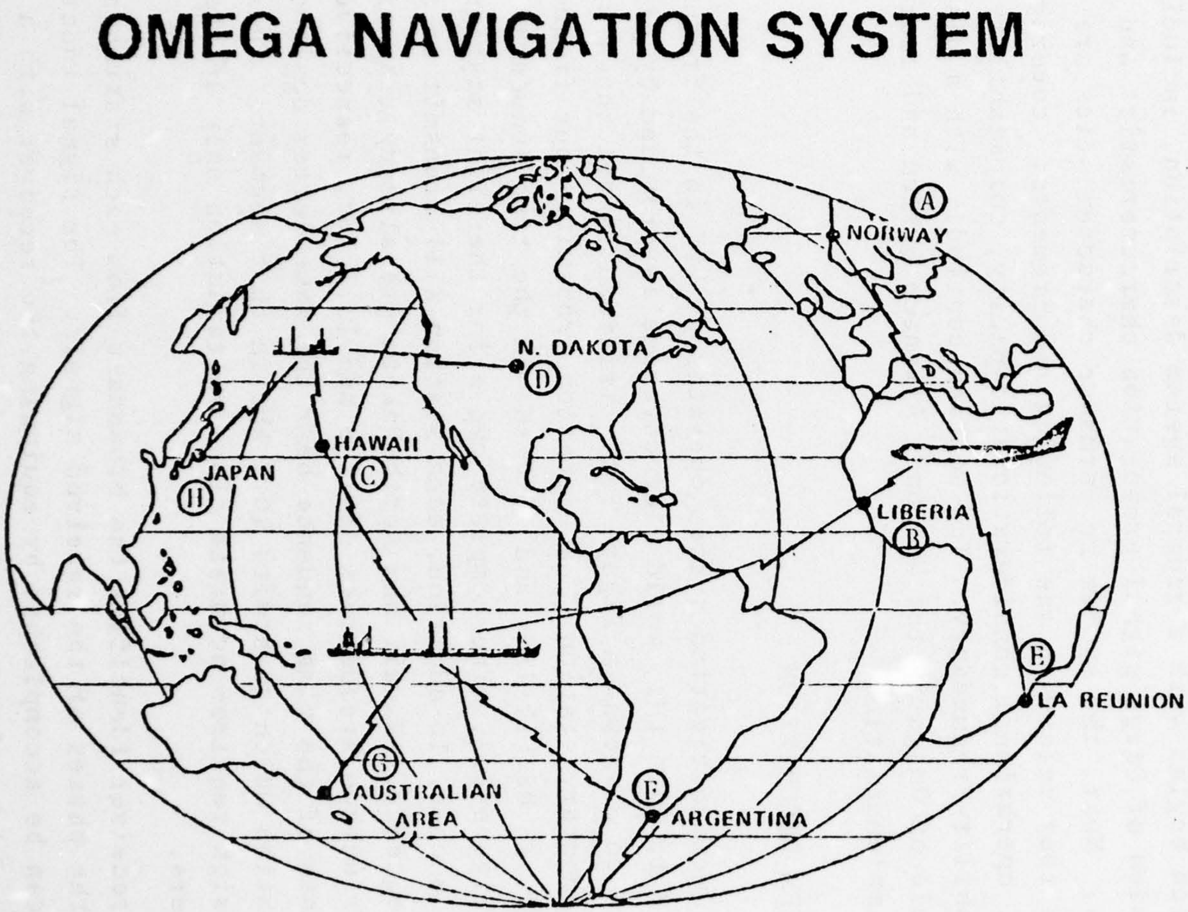


Figure 5.1 Eight worldwide stations providing all weather VLF radio navigation information brings Omega within the reach of all high seas users.

STATION \ SEGMENT	A	B	C	D	E	F	G	H
NORWAY (A)	10.2	13.6	11⅓	f_1	f_1	11.05	f_1	f_1
LIBERIA (B)	f_1	10.2	13.6	11⅓	f_1	f_1	11.05	f_1
HAWAII (C)	11.8	11.8	10.2	13.6	11⅓	11.8	11.8	11.05
N. DAKOTA (D)	11.05	13.1	13.1	10.2	13.6	11⅓	13.1	13.1
LA REUNION (E)	f_1	11.05	f_1	f_1	10.2	13.6	11⅓	f_1
ARGENTINA (F)	f_1	f_1	11.05	f_1	f_1	10.2	13.6	11⅓
SOUTH PACIFIC (G)* AREA	11⅓	f_1	f_1	11.05	f_1	f_1	10.2	13.6
JAPAN (H)	13.6	11⅓	f_1	f_1	11.05	f_1	f_1	10.2
Duration	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0

0.0 1.1 2.3 3.6 5.0 6.3 7.4 8.8 10.0

TIME (SECONDS)

* TRINIDAD TEMPORARILY FILLING G SLOT

POLICY FOR UNIQUE FREQUENCY TRANSMISSION IN UNUSED FORMAT SEGMENTS BEING FINALIZED

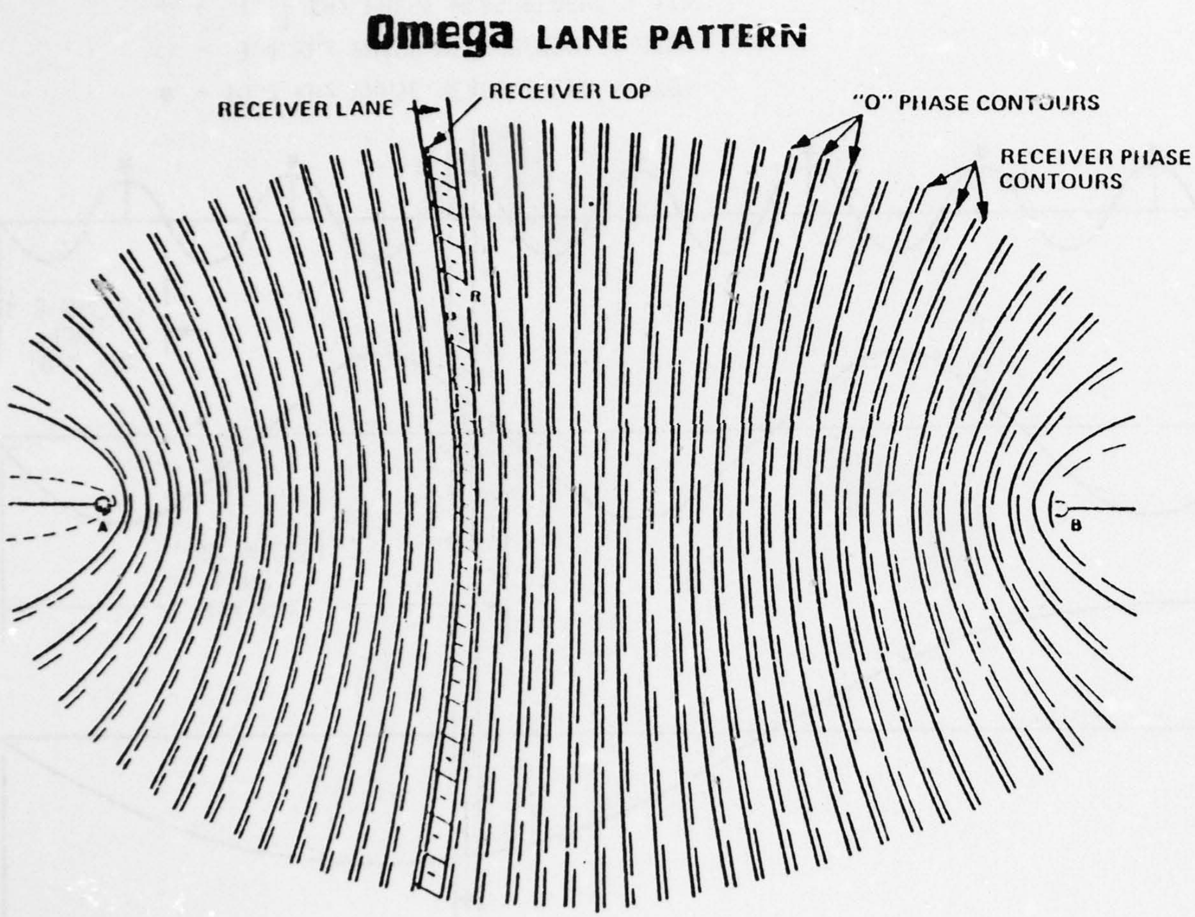
PROPOSED FULL FORMAT IS SHOWN:
- f_1 IS UNIQUE FREQUENCY AT EACH STATION
- 11.05 IS FOURTH NAVIGATION FREQUENCY

Figure 5.2 Omega Signal Transmission Format

each signal with an internal reference which oscillates at the 10.2 kHz frequency. The phase relationships between the reference oscillator and the temporally unique broadcasts are stored, and later the characteristics of the two signal transmisions are compared. Since the transmission are phase synchronized, the relative phase angle of a particular pair of signals that is received at a fixed location is a constant, and is dependent only on how much further it is to one of the transmitting stations than to the other. The same phase angle difference will be observed at all points having the same difference in distance to the two stations.

A hyperbola is defined as the locus of all points whose difference in distance from two foci is constant. A measurement at the receiver of the phase difference between transmissions from any two Omega stations yields a family of hyperbolic lines of constant phase relationship whose foci are at the two transmitting station locations, as shown in Figure 5.3. The loci of constant phase relationship are referred to as lines of position (LOP). An observer measuring a given phase relationship between two signals knows that he is located on a resultant LOP. If the navigator compares the received phase from at least three transmitting stations, two or more LOPs can be determined and a fix realized. Alternatively, an airborne clock can be synchronized to the transmitter clocks, yielding circular lines of position. Intersecting LOPs from only two transmitters now define a position fix. This mode of operation is referred to as ρ/ρ (rho/rho), and requires more sophisticated avionics.

Given that the Omega receiver is initially set to the correct lane at the beginning of travel and that continuous, correct phase measurements are made during travel, correct position will be known within the accuracy of the Omega system. Therefore, correct initialization or re-initialization of the receiver requires that position be known to one half of a lane width. The hyperbolic lane width at 10.2 kHz along the baseline is about 8 miles. Clearly, wider

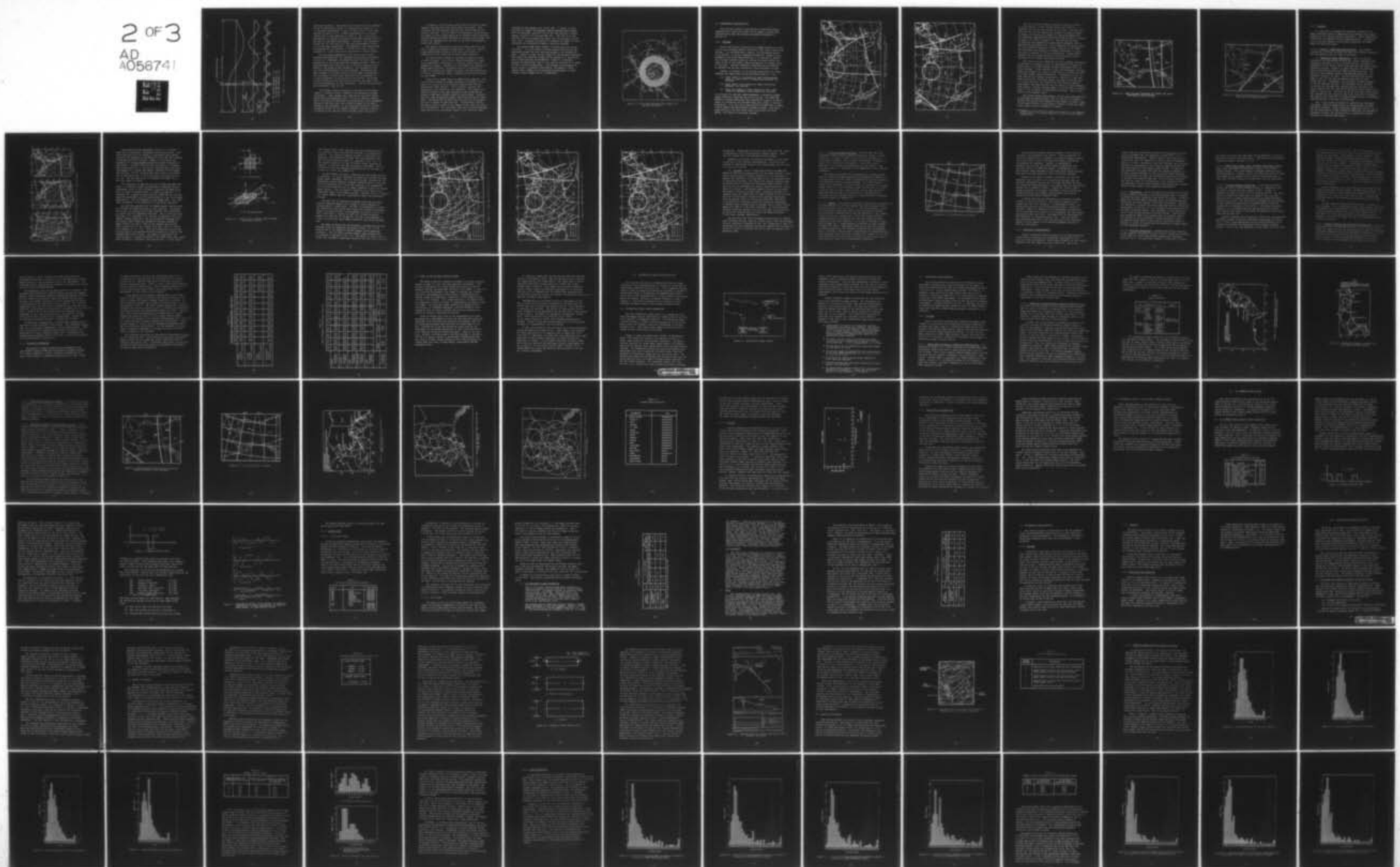


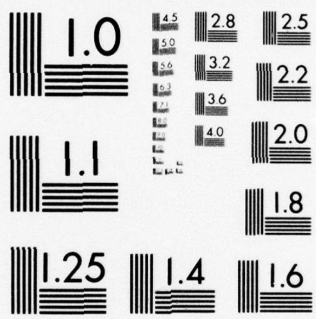
Source: Northrop Corporation, Electronics Division, <u>Omega Navigation System</u>, February, 1973.

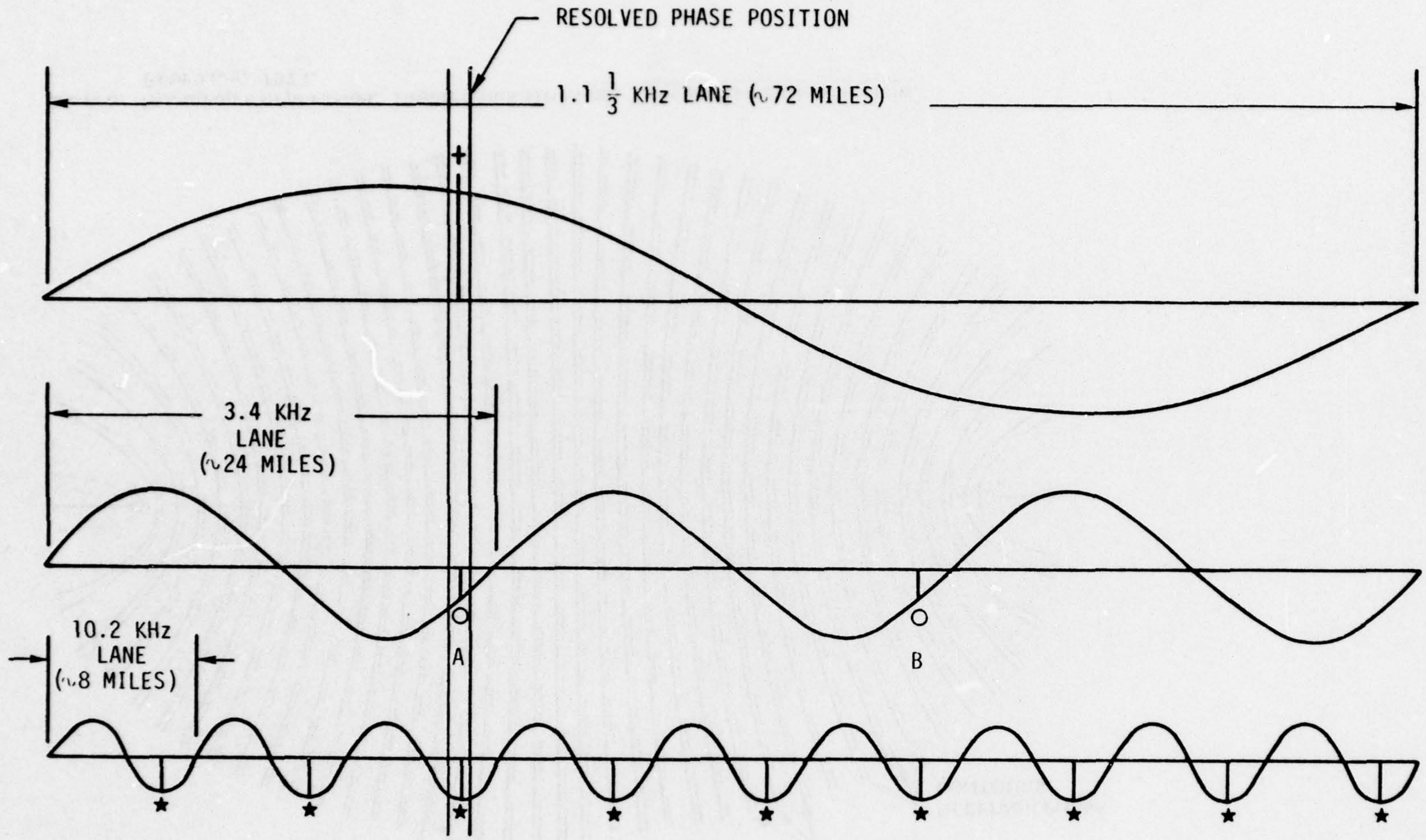
Figure 5.3 Omega Family of Hyperbolic Contours

AD-A056 741 SYSTEMS CONTROL INC PALO ALTO CALIF F/G 17/7
LORAN-C, OMEGA, AND DIFFERENTIAL OMEGA APPLIED TO THE CIVIL AIR--ETC(U)
APR 78 W HEINE, F G KARKALIK, E D MCCONKEY DOT-FA75WA-3662
UNCLASSIFIED FAA/RD-78-30-2 NL

2 OF 3
AD
A056741




1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3



★ - 10.2 KHz PHASE MEASUREMENT = 270°

O - 3.4 KHz PHASE MEASUREMENT = 330°

+ - $1.1\frac{1}{3}$ KHz PHASE MEASUREMENT = 110°

Figure 5.4 Multiple Frequency Lane Resolution

lanes are desirable. Wider lanes can be achieved by the combined use of the additional signals as illustrated in Figure 5.4. A 3.4 kHz phase measurement is used to resolve the 10.2 kHz phase position to point A or B. A phase measurement at 1.1-1/3 kHz resolves the 3.4 kHz ambiguity to point A. The 3.4 kHz phase measurement is obtained by taking the difference between the 10.2 kHz and 13.6 kHz phase measurements. Similarly, the difference between the 10.2 kHz and 11-1/3 kHz phase measurements yields a 1.1-1/3 kHz phase measurement. The hyperbolic lane widths along the baseline for 3.4 kHz and 1.1-1/3 kHz are 24 and 72 miles, respectively. Wider lanes can be achieved in a similar manner.

The long-range propagation of VLF waves is most easily understood mathematically by regarding the ground and ionosphere as walls of a waveguide, and considering the excitation and attenuation of the various possible propagation modes. When considering Omega phase stability, one of the most important parameters is the height of the ionosphere. The ionospheric layer acts as a moving boundary for the waveguide. This motion produces changes in the phase velocity of the Omega transmissions, and the degree to which these variations can be predicted is a prime determinant of the accuracy of the system. The height of the ionosphere varies with the time of day, the season, and with any disturbances in solar conditions. Some of the variations are predictable; some are not.

The largest regular variation in the phase of the Omega signals is related to daily changes in the ionosphere (diurnal variations). These changes are a function of the solar zenith angle along the propagation path. As the sun reaches a higher angle, the degree of ionization of the particles in the ionosphere increases, and this lowers the effective height of the upper surface of the waveguide. As the reflecting surface is lowered, the phase velocity of the signals increases, and there will be a dilation in the spacing of the resultant lines of position.

In addition to the diurnal effect there are smaller regular changes resulting from solar zenith angle variations. They fluctuate with the season of the year and the latitude of the receiver position. All the effects of ionospheric variation due to changes in solar zenith angle can be predicted quite accurately. Numerous methods have been developed to forecast these changes and present the information to the user in the form of propagation corrections (PPCs).

The regular fluctuation of observed signal phase does not pose a significant problem to Omega users. There are, however, large unpredictable variations that can cause trouble, as exemplified by the discussion of sudden phase anomalies.

Two other effects common to the Omega navigation system are the following. First of all, modal interference is found to be significant to the west of a station, located near the geomagnetic equator. Therefore, in this region the usability of Omega signals degrades. An example of this is reception of station B (Liberia) over CONUS. Secondly, the poor conductivity of the ice on Greenland creates shadowing of the Norway station (A) over CONUS.

There are two common types of sudden phase anomalies. The first, which is known as sudden ionospheric disturbance (SID), occurs as a result of X-ray radiation emitted from the sun during solar flare activity. This radiation increases the ionization of the D-layer of the ionosphere. This lowers the effective height of the upper boundary of the waveguide and causes a sharp phase advance along the sunlit paths. Recovery from this type disturbance usually takes from one-half to three hours. During periods of high solar activity this disturbance can occur a number of times each day. Alternatively, during periods of relative quiet in the sunspot cycle, they will occur very infrequently. The year 1968, which was a period of maximum solar activity for the present sunspot cycle, produced sudden

ionospheric disturbances 3.6% of the time. It should be noted that the two largest disturbances induced maximum phase changes of 70 microseconds, and only 0.3% of the time exhibited a phase change in excess of 20 microseconds [34]. 1981 will be a peak year for these occurrences and, hence, will be indicative of the worst case. Potential corrections to minimize the impact of these occurences are differential Omega or satellite warnings.

The second sudden phase anomaly is called polar cap absorption (PCA). It is the result of solar protons entering the magnetosphere around the earth and being guided to the geomagnetic poles. Figure 5.5 shows the PCA region for the Northern hemisphere. This lowers the effective height of the ionosphere in the auroral zone by approximately ten kilometers. There is a resultant decrease in phase delay, and it, too, must be interpreted in terms of line of position variations. The accuracy of the Omega navigation system is primarily determined by the degree to which regular phase changes can be predicted and the degree to which irregular phase changes can be accommodated.

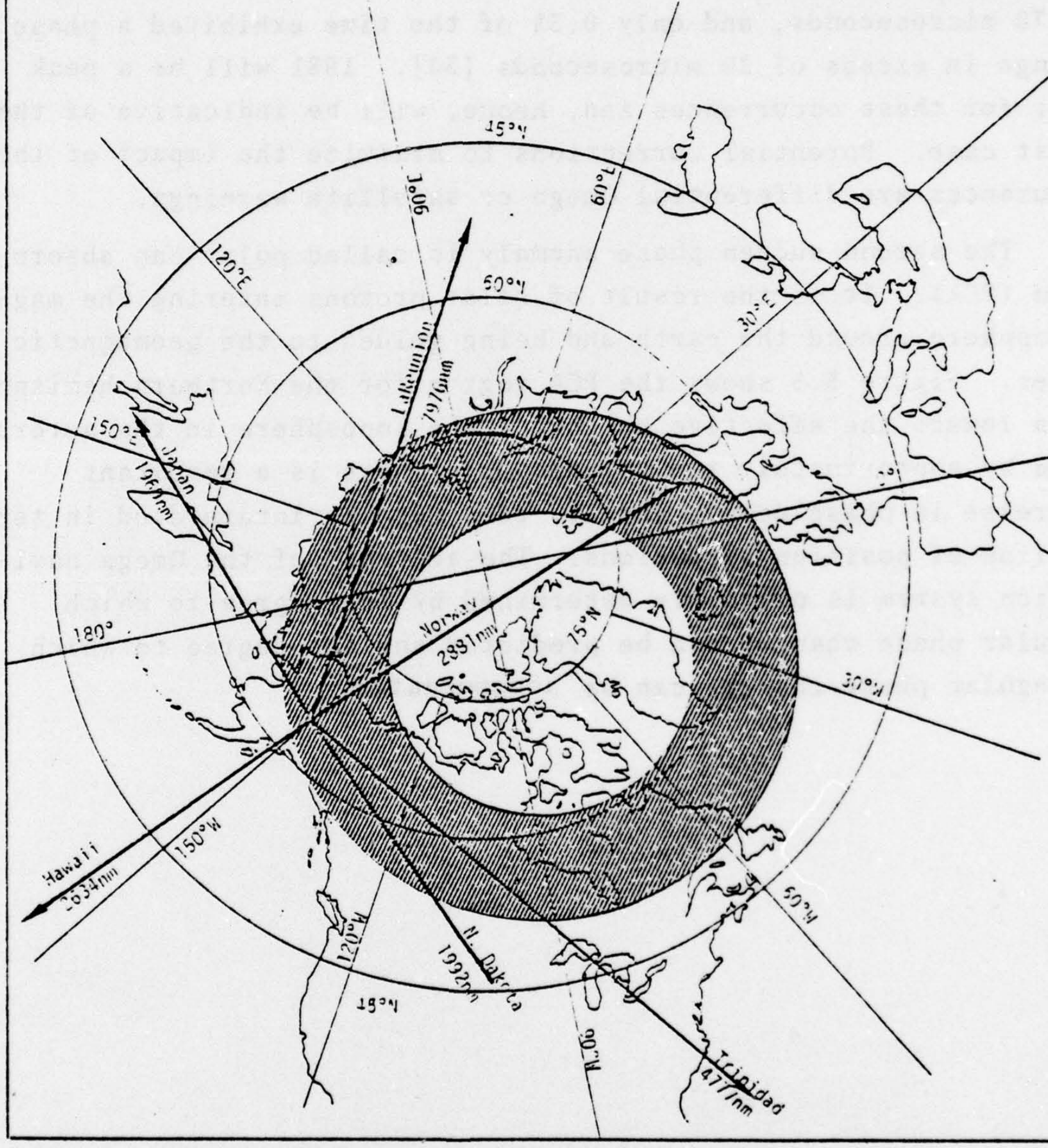


Figure 5.5 Polar Cap Absorption (PCA) Region for Northern Hemisphere

5.2 PERFORMANCE CHARACTERISTICS

This section presents a description of Omega performance characteristics and an assessment of the degree to which these characteristics meet the system requirements presented in Section III.

5.2.1 Coverage

One of the primary attributes of the Omega navigation system is the large coverage (global) provided by only eight transmitting stations. As indicated above, however, the transmitted signal is susceptible to various propagation anomalies. Based on known propagation and noise characteristics it is possible to predict the coverage available from each station for various dates and times of day as they affect signal availability at various points on the globe. The most optimistic prediction occurs midwinter at midnight and the most pessimistic occurs midsummer at noon.

Figures 5.6 through 5.9 are coverage predictions for CONUS, offshore and Alaska based on the following criteria: [35]

(1) Areas likely to be affected by near-field phenomena (that is, areas close to transmitting stations) are rejected.

(2) Areas likely to be affected by modal interference phenomena are rejected.

(3) Areas with signal to noise ratios less than -20dB (based on atmospheric noise models) are rejected.

In criterion (1), the near field phenomena is assumed to negate signal usability within 300 nmi of the station. The CONUS and offshore coverage predictions are presented in Figures 5.6 and 5.7. Figure 5.6 represents the midsummer noon case, which is the most pessimistic. Note that for a large portion of CONUS only stations C and D (Hawaii and North Dakota) provide coverage. Also for a large portion of the near-field region associated with North Dakota, only Hawaii (C) provides coverage.

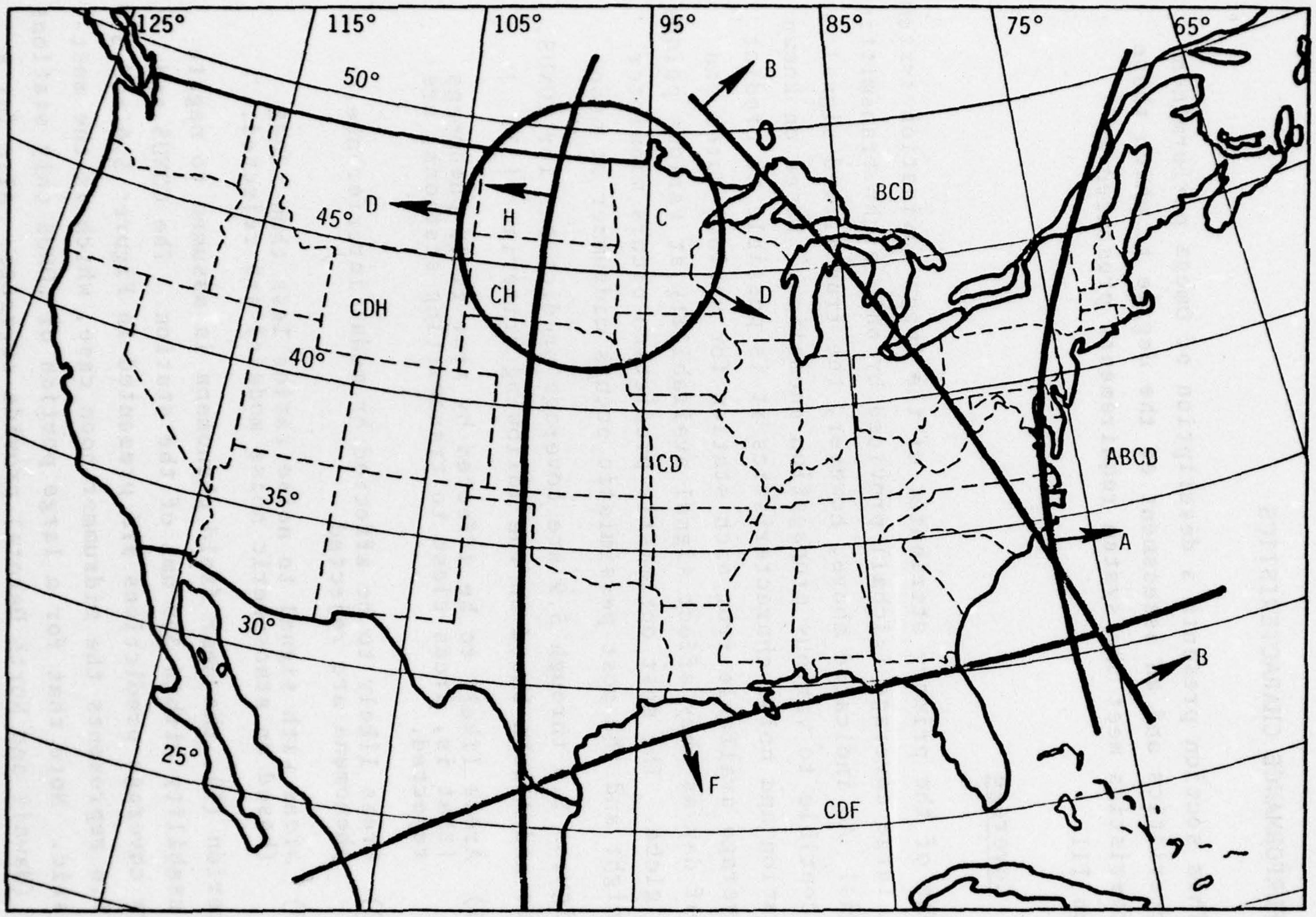


Figure 5.6 Omega Coverage Prediction for CONUS and CONUS Off-shore at Noon Midsummer

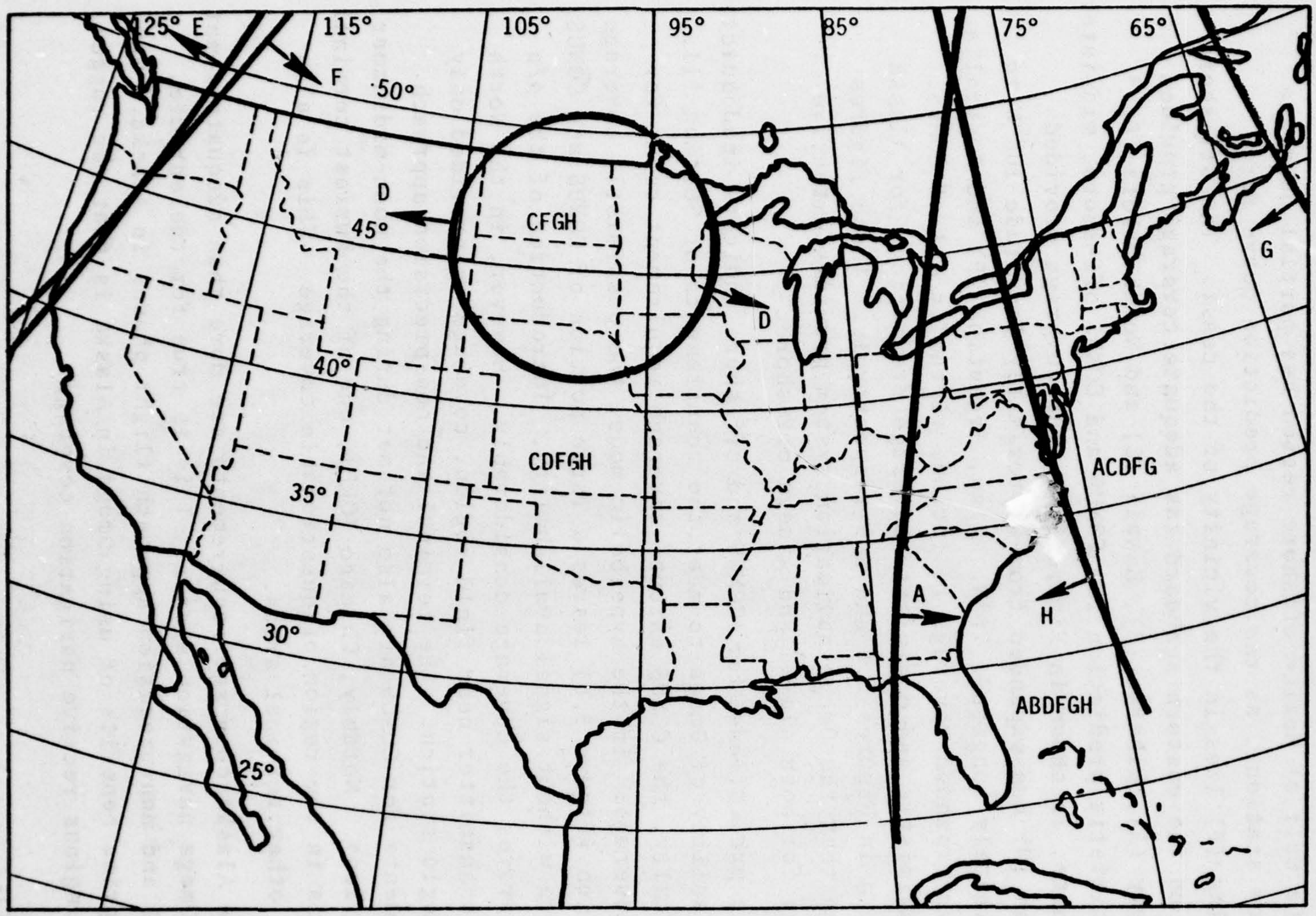


Figure 5.7 Omega Coverage Prediction for CONUS and CONUS Off-shore at Midnight Midwinter

The Gulf of Mexico offshore region has partial coverage by three stations, as the coverage prediction curve for Argentina (F) lies in the vicinity of the coast. The off-shore region on the eastern seaboard has adequate coverage provided by Norway (A), Liberia (B), Hawaii (C) and North Dakota (D).* The optimistic prediction for CONUS and CONUS off-shore, midwinter at midnite, is shown in Figure 5.7. The coverage provided by Japan (H) has expanded from approximatly longitude 100°W to approximately longitude 76°W. Also, Argentina (F) and Australia (G) have expanded coverage to include virtually all of CONUS. The pessimistic and optimistic coverage predictions for Alaska are shown in Figures 5.8 and 5.9 respectively. These figures indicate that the Omega navigation system provides extensive coverage for both Alaska and Alaska off-shore.

The predictions for CONUS and off-shore indicate inadequacies in the ability of Omega to meet the requirements of Section III. Specifically, the CONUS enroute coverage requirement calls for total coverage. In the hyperbolic mode, the pessimistic coverage prediction (Figure 5.6) leaves a large portion of CONUS and CONUS off-shore without signal availability. Introduction of the ρ/ρ mode improves the coverage considerably. However, in the North Dakota transmitter near field region, coverage is provided only by a single station. The terminal and non-precision approach requirements for CONUS are also not met during the noon-midsummer time periods. Notably, Chicago (ORD), one of the busiest terminal areas, is in the region of questionable coverage. This is also true of other terminal areas.

The Alaska coverage requirements are more than adequately met by the Omega navigation system. This is true for the enroute, terminal and non-precision approach flight phases in Alaska. One of the prime benefits of using Omega in Alaska is that the rugged remote regions receive navigation coverage.

* Trinidad is not included in these plots since it is a temporary station and will be discontinued on or before Australia begins transmitting.

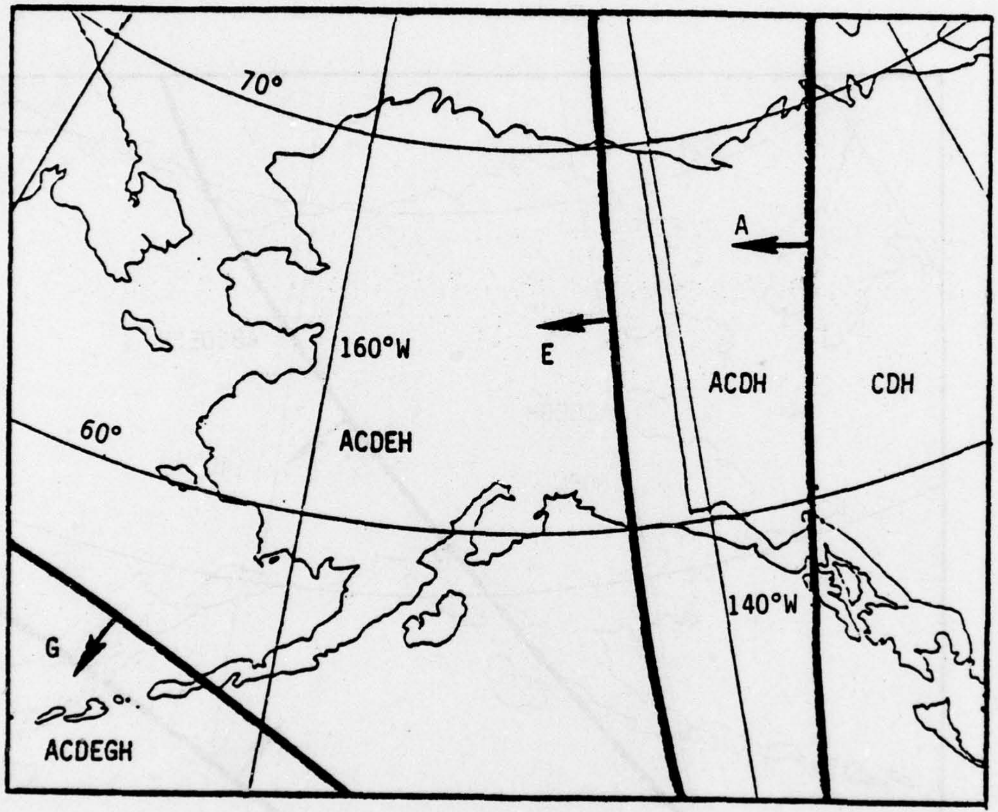


Figure 5.8 Omega Coverage Prediction for Alaska and Alaska Off-Shore at Noon Midsummer

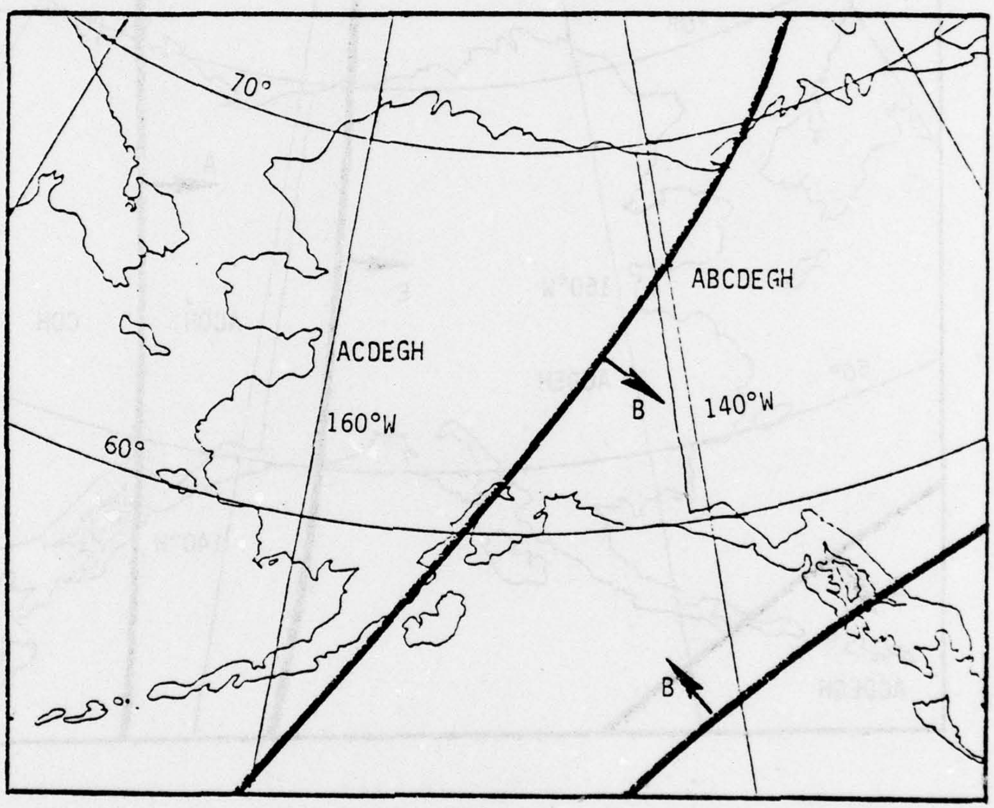


Figure 5.9 Omega Coverage Prediction for Alaska and Alaska Off-Shore at Midnight Midwinter

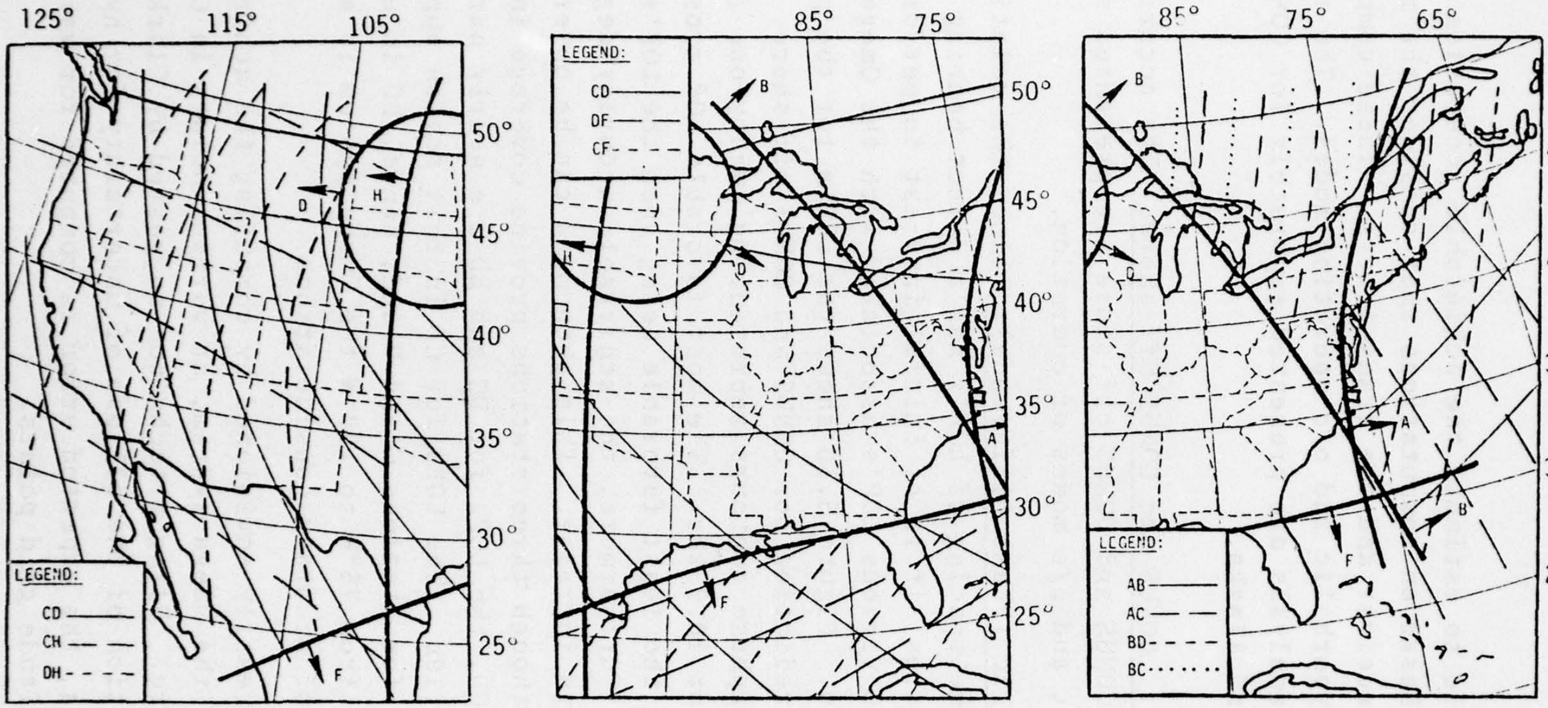
5.2.2 Accuracy

It is possible to estimate the achievable accuracies for Omega navigation based on computations that consider the relative geometry of the receiver and the transmitters. These computations will differ for hyperbolic and ρ/ρ operating modes. The results of this accuracy analysis are presented separately for CONUS, CONUS off-shore and Alaska.

5.2.2.1 Accuracy: CONUS and CONUS Off-shore. The accuracy requirements for CONUS and CONUS off-shore are presented separately for the hyperbolic and ρ/ρ modes of operation.

(1) Hyperbolic (Phase Difference). Since the relative orientation and the spacing of LOP's has a direct bearing on the achievable accuracies, it is of initial interest to perform an examination of the various LOP's associated with the Omega stations providing coverage. Figure 5.10 shows the LOP's for the pessimistic coverage prediction for CONUS and CONUS off-shore. The LOP plots are equiphase contours representing twenty-one (21) hyperbolic lanes at 10.2 kHz. The most favorable LOP crossing angle is 90° with the least favorable being when the LOP's become parallel. Furthermore, the achievable accuracy degrades as the LOP spacings increase. This phenomena can be observed by noting that although three stations provide coverage in the region labelled BCD, the LOPs for BC and BD are nearly parallel as shown in Figure 5.10c. The LOPs for CD in this region appear along the extended base for stations C and D and, hence, DC is unstable. This implies that from 75°W to 100°W the Omega system is essentially unusable because of accuracy considerations.

This is more easily envisioned by computing the achievable accuracies, using the Omega system, at various points in CONUS and CONUS off-shore. Using a technique suggested by Clark [36] for the determination of the ellipse of uncertainty for hyperbolic navigation systems, the expected error is computed for various latitude and longitude grid points.



a) Western CONUS

b) Central CONUS and Gulf of Mexico Offshore

c) CONUS East Coast Off-shore and Great Lakes area

Figure 5.10 CONUS Omega LOP's for Noon Midsummer

Associated with the measurement of LOP's is a certain error due to transmitter, propagation and receiver noise. This error translates into an ellipse of uncertainty whose characteristics are dependent on the manner in which the LOP's combine to provide a position estimate. Figure 5.11 indicates two potential LOP crossing angles and the associated ellipsoid of uncertainty. Consider that the LOP's are subject to a measurement error given by $\pm$ d. For the 90° crossing angle the ellipsoid appears as a circle with radius d centered at the nominal LOP crossing. The 40° crossing angle gives rise to an ellipse with a semi-major axis, A, of 2.11d, and a semi-minor axis, B, of .75d. The semi-major axis is oriented at an angle, ϕ, of 60° with respect to north.

This technique was applied over all of CONUS and CONUS off-shore. A literature search was performed to determine the LOP measurement error, d, in an attempt to quantify the Omega accuracies in terms of nautical miles. A report by Swanson [37] indicates for a signal-to-noise ratio of -18dB that the expected Omega LOP measurement error is on the order of 1 nmi for airborne applications. This corresponds to a one sigma value. The 1 nmi value corresponds to the parameter d in the above discussion.

The data base generated for the Omega accuracy analysis over all of CONUS and CONUS off-shore is very extensive. In essence the accuracy is computed for several potential LOP combinations at various specific geographic locations. Due to the size of the data base it is included in its entirety in Appendix B with only summary comments made here. For the pessimistic coverage case the western CONUS region has navigation coverage provided by Omega stations C,D and H. Only in the northern half of this region (above 40°N) is the accuracy less than 2 nmi (1σ) (Table B.15, Appendix B, Vol. III). This can be expected since the LOP crossing angles are degrading from the favorable 90° value in the southern half of this region. The impact of unfavorable LOP crossing angles is further evidenced in the CONUS Great Lakes region where reception is available from stations BCD. In this region

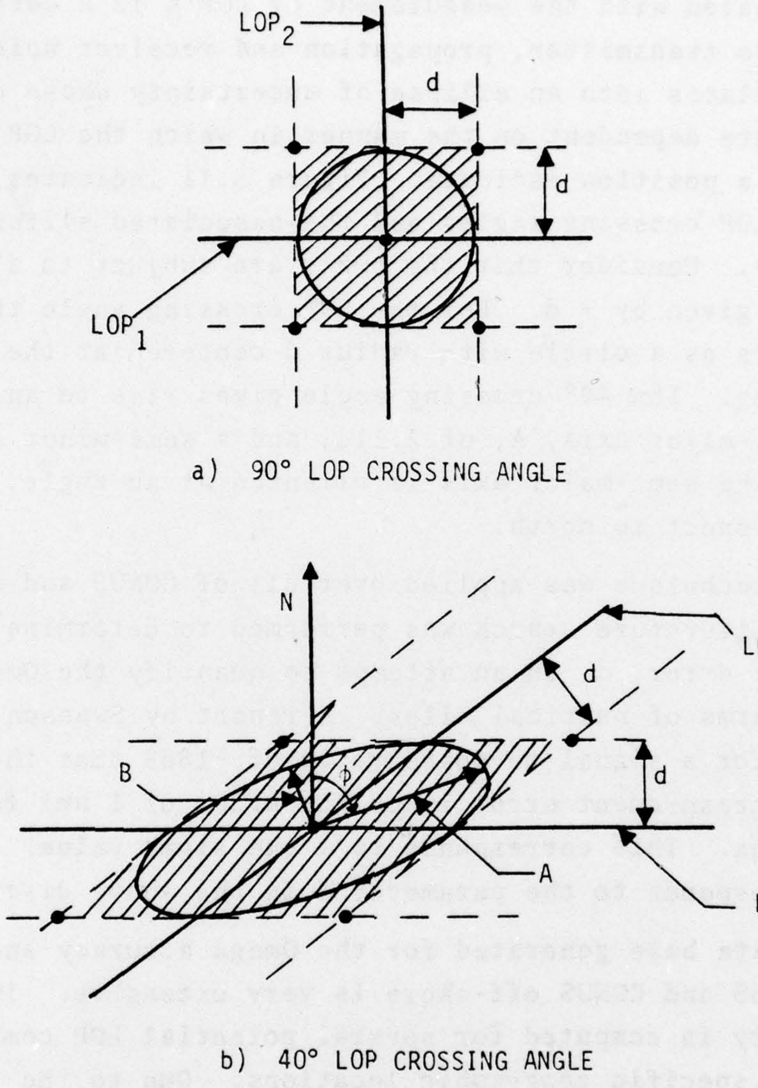


Figure 5.11 Impact of LOP Crossing Angle on Omega Uncertainty Ellipse

(see Figure 5.10c), which coincides with the extended baseline for stations C and D, the LOPs are observed to be essentially parallel. The resultant degraded accuracy is observed in the quantities associated with latitude 45°N and longitudes 85°W and 75°W as presented in Table B.1, Appendix B, Vol. III. In the offshore region of the Gulf of Mexico, where reception of station F is possible, the LOP crossings are favorable. This is reflected in that the achievable accuracies are on the order of 1.3 nmi to 1.4 nmi (1σ) (Table B.1).

On the Atlantic sea-coast, reception from four Omega stations is available. As can be observed in Figure 5.10, the LOP crossings angles appear favorable. With all four stations transmitting, the uncertainty ellipse displays favorable characteristics at latitude 40°N and longitude 75°W. Of further interest is an examination of the error characteristics as signal reception is lost for various Omega stations. Loss of station A (Norway) or B (Liberia) has a significant impact on the Omega accuracy. However, loss of C (Hawaii) or D (North Dakota) does not significantly impact the achievable accuracy.

The LOP's for the optimistic coverage prediction are shown on three separate figures in an attempt to avoid confusion by placing them on a single plot. The LOP's corresponding to C and D are indicated on each of the three figures as a point of reference. Figure 5.12 shows the LOP's corresponding to C and D, D and F, D and G, and D and H. Figure 5.13 shows CD, CF and CH whereas, Figure 5.14 shows CD, FG, FH and GH. The LOP's corresponding to C and G are not shown since CONUS essentially lies on the extended base.

The Omega accuracies for the optimistic coverage case are also computed using the techniques described by Clark [36]. Of interest now is the impact of station outages on the predicted accuracies. Loss of single station outages, taken sequentially, is presented in Appendix B, Vol. III. The impact of single station outage does not appear significant except in the case of the loss of F

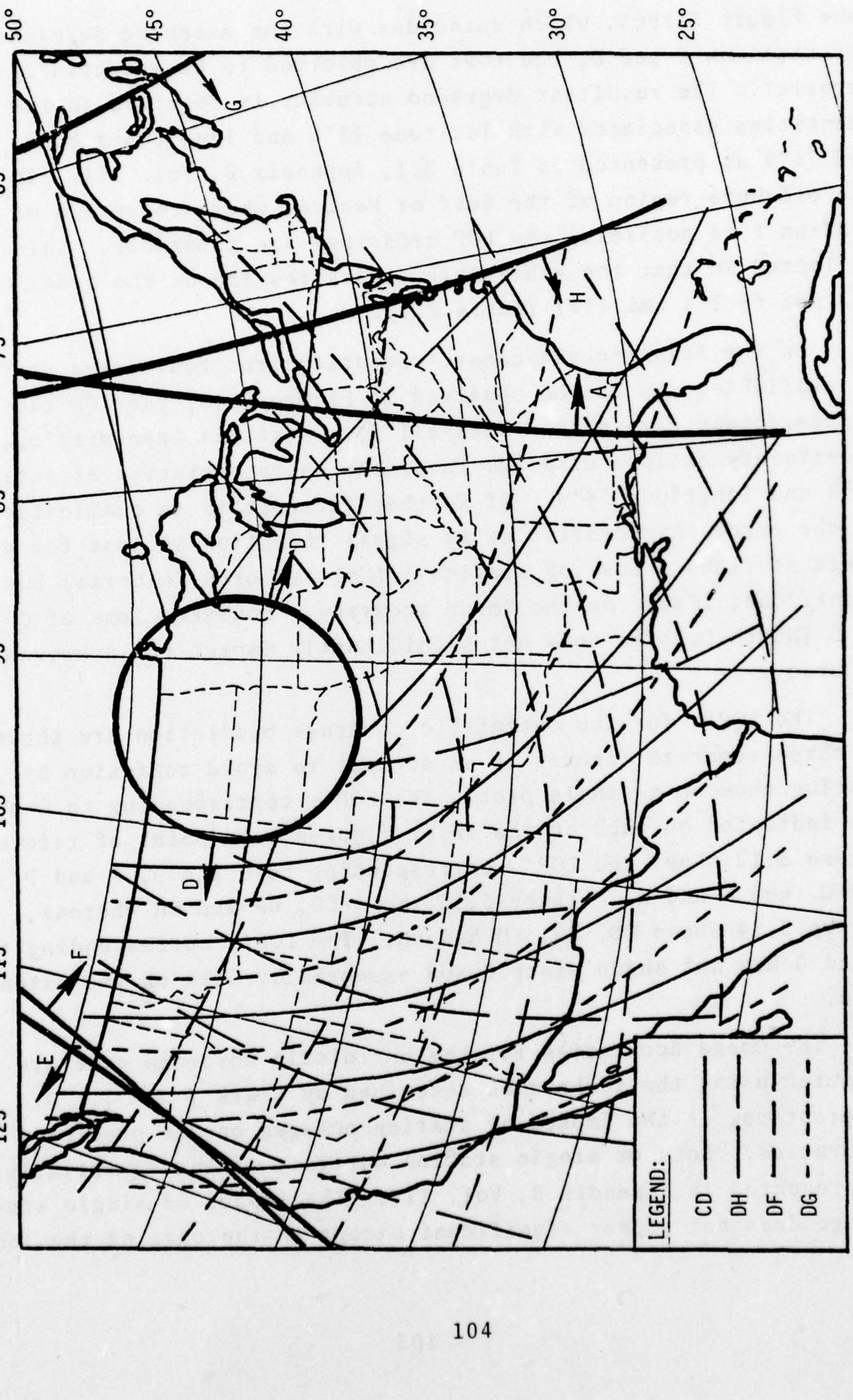


Figure 5.12 CONUS Omega LOP's CD, DF, DG AND DH

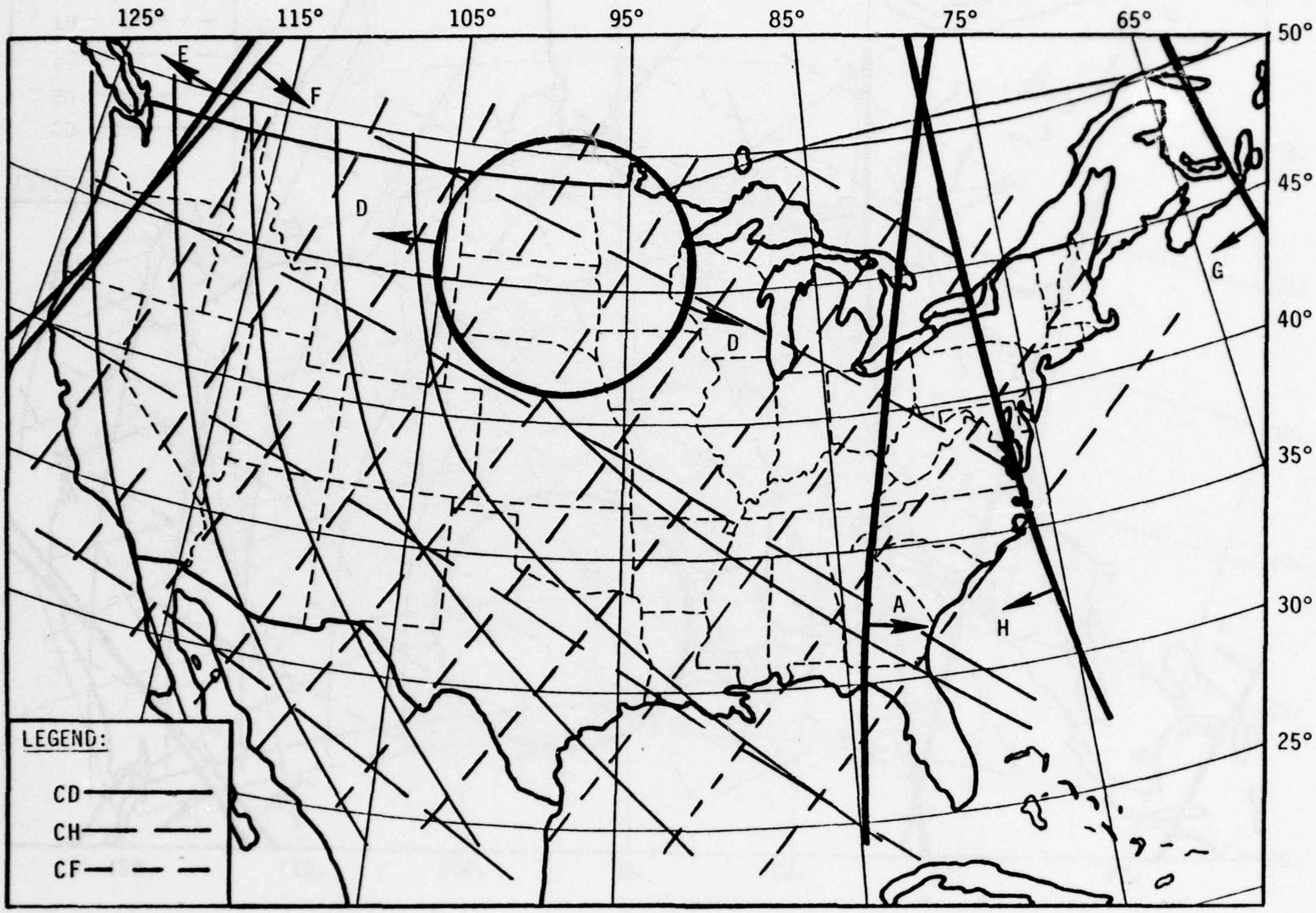


Figure 5.13 CONUS Omega LOP's CD, CF, and CH

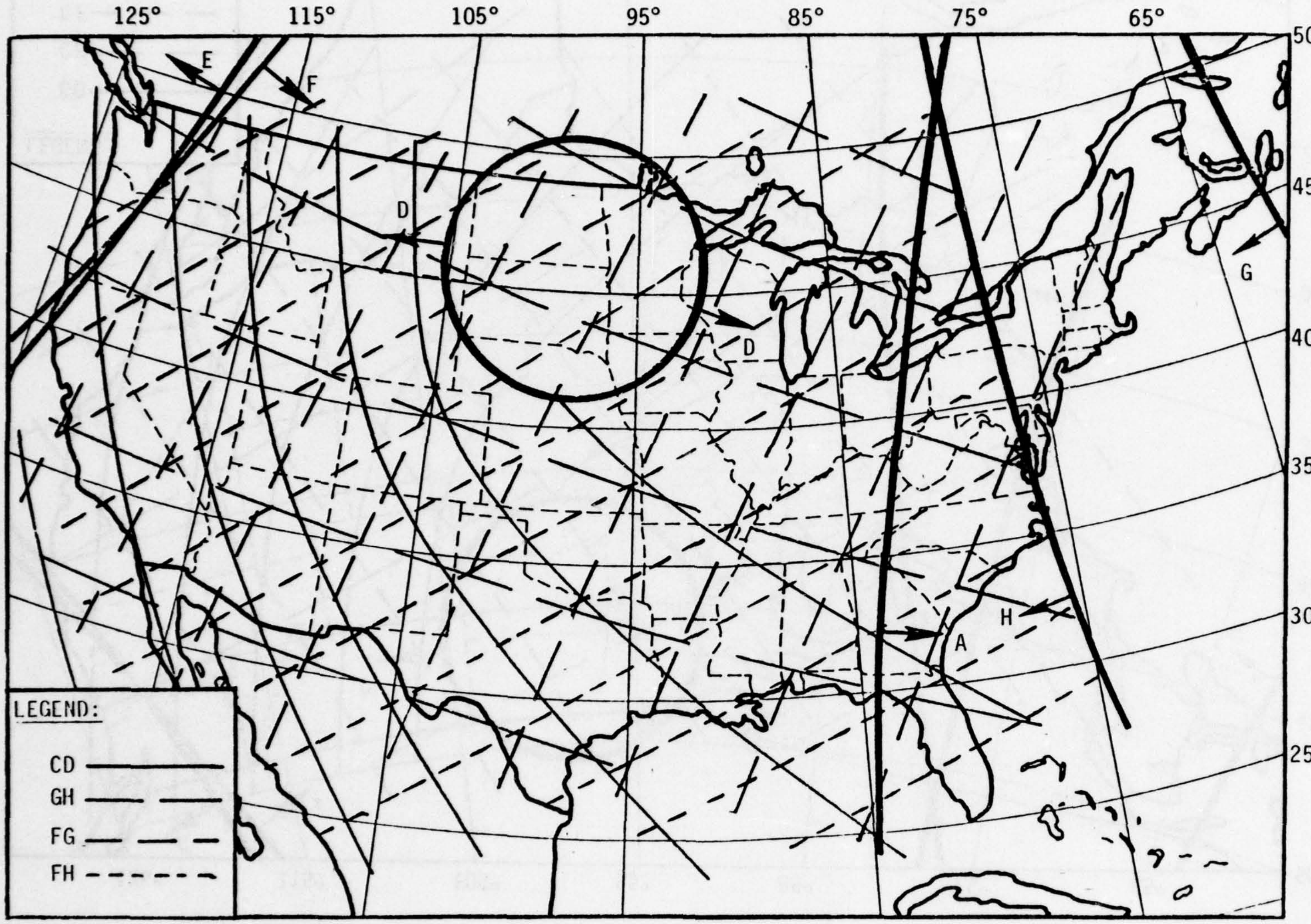


Figure 5.14 CONUS Omega LOP's CD, FG, FH and GH

(Argentina). Examination of the LOP plots shows that LOP's made in conjunction with F form favorable crossing angles. Hence, loss of F leaves LOP's with degraded crossing angles.

Appendix B also shows the expected accuracies in the event of the loss of two stations simultaneously. The loss of two stations is significant except in the simultaneous loss of C and D, D and G, or G and H.

(2) ρ/ρ Mode. Since a significant portion of CONUS and CONUS off-shore has reception from only two Omega stations, according to the pessimistic coverage prediction, it is desirable to examine the feasibility of using Omega in the ρ/ρ navigation mode. As indicated previously, this requires an accurate onboard clock to measure time of arrival from individual Omega stations. The LOP's in the ρ/ρ mode appear as equally spaced concentric circles about the stations. The primary geometric effect on achievable accuracies is the LOP crossing angle. Expected accuracies are computed using all combinations of Omega stations in the ρ/ρ mode for both the pessimistic and optimistic coverage predictions. Since an onboard clock is utilized and additional information is available the achievable accuracies display an improvement. A tradeoff exists between using an onboard clock to fully utilize Omega over CONUS or using other techniques. In the pessimistic coverage situation, however, total ρ/ρ coverage is not available and along the extended base of C and D the Omega accuracies, in this mode, degrade significantly.

The accuracies for the ρ/ρ navigation mode using all combinations of Omega stations, when two, three, four or five are available, are also presented in Appendix B, Vol. III. Comparison of these ρ/ρ accuracies with the hyperbolic accuracies indicate that in almost all cases the accuracy is improved for the ρ/ρ mode as opposed to the hyperbolic mode.

5.2.2.2 Alaska and Alaska Off-Shore. Not only does the Omega navigation system provide excellent coverage in Alaska, as shown previously in Figures 5.8 and 5.9, but the LOP crossings tend to be quite favorable. This is shown, for example, in Figure 5.15 where the AC and DH LOP's are plotted. These LOP's can be observed to be essentially perpendicular to one another. This favorable geometry is reflected in the computation of the expected accuracies.

The expected accuracies for the pessimistic coverage prediction for Alaska and Alaska Off-shore are presented in Appendix B. A similar analysis as for CONUS is performed in that the accuracies are computed for various station outages. For single station outages the degradation in the accuracies is observed to be insignificant (less than 2 nmi) everywhere except for the loss of A and E, A and H, C and E, D and F, and E and H. In the last case error magnitudes greater than 2 nmi appear only in the Bering Sea. Accuracies for all stations available in the optimistic prediction are also presented in Appendix B.

5.2.2.3 Summary. The accuracy assessment discussed here considers only the contribution from the LOP spacings and crossing angles given a phase measurement error of 1 nmi (1σ). With these accuracy values it is possible to determine regions where the accuracy exceeds the requirement threshold due to poor LOP geometries. For example, in the pessimistic coverage case, a particular region displays degraded achievable accuracies since the LOPs defined by three transmitters are nearly parallel. It is also of interest to note that although the ρ/ρ mode generally alleviates the lack of Omega coverage over CONUS, significant errors can and do arise because of adverse geometries. For example, along the base and extended base of stations C (Hawaii) and D (North Dakota) the expected accuracies approach 50 nmi, as shown in Table B.18, Appendix B, Vol. III. These stations are the only ones providing coverage over a significant portion of CONUS for the pessimistic predictions.

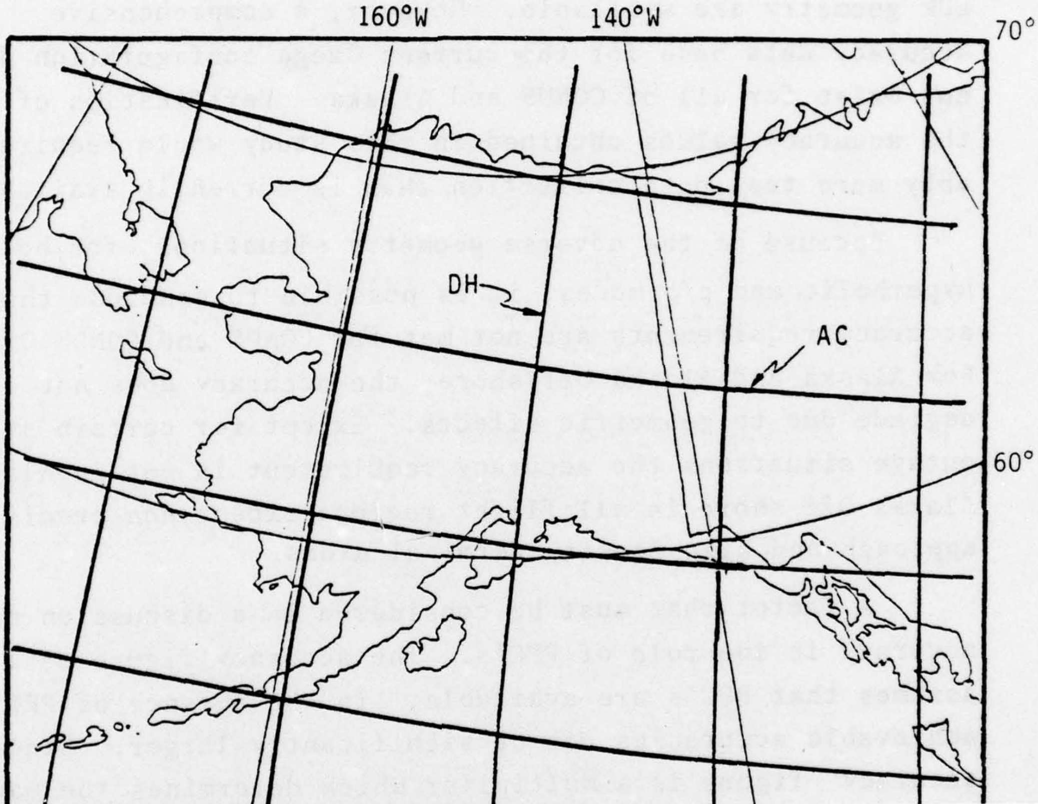


Figure 5.15 A-C and D-H LOP's in Alaska

The theoretical accuracy values obtained in this study are consistent with published test results. Several documents [38, 39,40,41] indicate that, in general, the expected Omega accuracies are on the order of 1 to 2 nmi where good signal coverage and LOP geometry are available. However, a comprehensive accuracy data base for the current Omega configuration does not exist for all of CONUS and Alaska. Verification of all the accuracy values obtained in this study would require considerably more test data collection than is currently available.

Because of the adverse geometry situations, for both the hyperbolic and ρ/ρ modes, it is possible to conclude that the accuracy requirements are not met for CONUS and CONUS Off-shore. For Alaska and Alaska Off-shore, the accuracy does not significantly degrade due to geometric effects. Except for certain station outage situations the accuracy requirement is met in Alaska and Alaska Off-shore in all flight regions except non-precision approach and high density terminal areas.

A factor that must be considered in a discussion of Omega accuracy is the role of PPC's. The accuracy figure of 1 nmi assumes that PPC's are available. In the absence of PPC's, the achievable accuracies can be significantly larger. Since the accuracy figure is a multiplier which determines the magnitude of the resulting error ellipse it is conceivable that the accuracy requirement could not be met. The impact for the requirement of PPC capability is increased avionics cost. Low cost avionics may be manufactured that do not have some form of PPC capability, however, at the expense of not achieving adequate accuracy to meet the requirements.

5.2.3 Operational Considerations

Several operational factors peculiar to the Omega navigation system and not itemized in the navigation requirements of Section III must be considered. These relate primarily to the avionics capability and thus impact the cost to the user. One of the

factors that has already been discussed in the previous section is the requirement for the capability to apply PPC's to the Omega phase measurements. Another factor is that some low cost avionics may have the capability to receive only one frequency such as 10.2 kHz. Reception of only one frequency can potentially degrade the performance of the airborne navigation system such that the navigation requirements cannot be met. In addition, the capability to receive more than one frequency provides, in essence, system redundancy in that if one particular frequency is not available the other two frequencies would remain available to perform the navigation function. The two factors discussed here must be taken into consideration in the avionics design. The remainder of this section presents other operational considerations as they relate to the navigation requirements.

5.2.3.1 Flexibility. One of the inherent attributes of the Omega system is that it operates in an area navigation mode as opposed to requiring flight operations from station to station. In theory, Omega also provides global coverage, hence, providing navigation between any two fixes whether or not they are charted. Therefore, the capability to specify any route (and hence meet the flexibility requirements of Section 3.4.1) is available as an integral part of the Omega navigation system. Full advantage of this flexibility can be taken through appropriate avionics design. Specifically, area navigation (RNAV) type software must be available onboard the aircraft to allow execution of flights along RNAV routes. In addition, flight check service must be provided in areas of interest to ensure the availability and usability of Omega signals for IFR navigation purposes.

5.2.3.2 Position Presentation. Although Omega-derived position is most naturally displayed in terms of LOP's, appropriate software can be added to satisfy the position presentation requirement (Section 3.4.2). The additional software is necessary to convert

LOP fixes to latitude and longitude, and subsequently to calculate deviations from the prescribed course. (See also the corresponding section for Loran-C, Section 4.2.3.2).

5.2.3.3 Common Input Format, Pilot Workload, and Failure Alerts. These three requirement subcategories relate to the aircraft avionics design. The actual design is dependent upon the individual manufacturers. However, due to the competitive nature of hardware marketing, an attempt will be made by the manufacturers to cause their avionics design to be consistent with the requirements.

5.2.3.4 Position Ambiguity Resolution. In the Omega navigation system, the relative phase between any pair of transmitters does not define a unique LOP, but a family of LOPs. Figure 5.3 indicates the family of LOP's for the station pair A-B. The phase space is divided into lanes which are bound by the cross-over points of the two signals representing the zero phase-difference contours of the pair. The lane width is dependent on the frequency of the transmitted signal and the subtended angle between the transmitters as measured at the receiver. For Omega to function properly, it is necessary that the lane ambiguity be resolved. This requires the process of selecting the appropriate lane within which the receiver lies.

Several techniques can be applied to resolve the lane ambiguity, and hence to meet the position resolution requirement of Section 3.4.7. First, given appropriate initialization parameters it is possible to determine the appropriate lane through a counting process. For the 10.2 kHz frequency the lane width is on the order

of 8 nmi and for 13.6 kHz the lane width is approximately 6 nmi. For maneuvering aircraft it is clear that the potential exists for losing the lane count. Lane ambiguity can be reduced by lower frequency signals, thereby increasing the lane width. A technique that will produce this feature is frequency-differencing between the 13.6 kHz and 10.2 kHz signals. If the phase synchronization between all the signals is adjusted so that an LOP of the 13.6 kHz signal coincides with an LOP of the 10.2 kHz signal, a wave pattern is obtained in which every third LOP of the lower frequency concides with every fourth LOP of the upper one. The coincidental LOP's define a pattern of broader lanes extending over three lanes of the 10.2 kHz pattern, or 24 nmi. This corresponds to an apparent transmitter frequency of 3.4 kHz. Figure 5.14 depicts this technique schematically.

Further expansion of the lane width can be achieved through further application of the frequency differencing technique. As indicated previously, Omega signals are transmitted at the three frequencies, 10.2 kHz, 11-1/3 kHz and 13.6 kHz. Differencing techniques between these frequencies yield potential lane widths of 72 nmi.

The lane counting technique described above is subject to lane slippage. This is particularly true of the smaller lane widths. This problem can be alleviated, to a great extent through the use of dead reckoning equipment such as air data, doppler or INS. In this manner the dead-reckoning system will retain a position estimate in the event of signal loss due to a sudden phase anomaly or other disturbance.

5.2.3.5 <u>System Activation and Position Fix Update Rate</u>. The system acquisition factors discussed in Section 4.2.3.5 for the Loran-C system also apply here for the Omega navigation system. The Minimum Operational Standards and Minimum Performance Standards [42] specify that the synchronization time for the Omega system be three (3) minutes at a S/N of one station/three frequencies of at least 0 dB. Although this acquisition time for Omega is less than

that of Loran-C it fails to meet the system acquisition time requirements specified in Section 3.4.8. With additional avionics sophistication, it may be possible to meet the requirements. The increased avionics sophistication translates into higher user system costs which are not addressed here.

The commutation cycle of the Omega system is 10 seconds. This represents the minimum time interval between position fix updates. However, various receivers combine the Omega measurements in different ways which can potentially reduce the update time interval. Consider, for example, stations A, C and G forming LOPs AC and CG. At a frequency of 10.2 kHz LOP AC can be formed 3.4 sec. into the commutation cycle and LOP CG can be formed 8.6 sec. into the cycle. Therefore, using AC and CG a position fix is obtained 8.6 sec. into the cycle. Using CG and AC of the next cycle, the position fix is obtainable 3.4 sec. into the next cycle. The intervals between position fixes are 5.2 and 4.8 sec., respectively. As more LOPs are available the update interval is reduced even further.

An additional consideration is the potential availability of some form of dead reckoning or rate aiding. This capability implies that not all navigation information is lost between updates. Therefore, the position fix updating characteristic of Omega is not equivalent to a total navigation signal loss. Furthermore, the maximum expected update interval of 10 sec. is within the reacquisition times specified in Section III.

5.2.4 Reliability/Redundancy

The question of Omega reliability and redundancy is of considerable concern because of the extensive coverage provided by a single transmitter. Hence, outage of a transmitter can have a severe impact on navigation operations in the NAS. Since

the Omega navigation system is not fully operational as yet it is difficult to ascertain what the reliability of the overall system will be. Some data does exist in the form of percent monthly transmitting time. Table 5.1 and 5.2 show these quantities for 1974 and 1975 respectively. These represent conditions prior to full operational status, hence, it is conceivable that an improvement in these values can be expected.

Since Omega provides adequate coverage only in the Alaska region (of the regions of interest) the values in Table 5.2 are used to estimate the impact of Omega reliability in Alaska. In the pessimistic coverage case (Figure 5.8) only station E is not represented in Table 5. The yearly average figures are, therefore, averaged over the five stations to have a transmission probability, taking into account only unscheduled outages, of 0.9992. Applying this value in the determination of the probability of station outages the values of 3.98×10^{-3} for single station outage, 6.38×10^{-6} for outage of two stations simultaneously and 5.112×10^{-9} for outage of three stations simultaneously are obtained. Single station outage is critical for the southeastern panhandle where only three stations are available. For the remainder of Alaska, there is adequate redundancy in coverage such that reliability would not appear to be a problem.

The preceding discussion was concerned with unscheduled outages of the transmitter only. SID's and PCA's have a more significant impact in that they can affect the signal reliability from all available stations at once. Insufficient data exists at this time to make an evaluation of the impact of ionospheric disturbances on overall Omega system reliability.

Table 5.1

% MONTHLY TRANSMITTING TIME 1974

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
A	NORWAY												
	Unscheduled	99.94	99.96	99.70	99.98	99.79	99.97	99.96	99.98	99.95	99.98	99.70	99.98
	Scheduled & Unscheduled	99.94	99.96	99.70	99.98	99.79	99.83	99.96	99.98	96.94	99.98	98.66	99.98
B	TRINIDAD												
	Unscheduled	98.88	99.97	99.99	99.94	99.79	99.94	99.97	99.95	99.41	99.97	99.79	99.98
	Scheduled & Unscheduled	98.88	99.97	99.99	99.94	98.51	99.94	99.97	99.95	99.41	99.29	99.79	99.98
C	HAWAII												
	Unscheduled										99.92	99.62	99.93
	Scheduled & Unscheduled										36.24	91.54	94.36
D	NORTH DAKOTA												
	Unscheduled	99.57	99.97	99.99	99.89	99.94	99.40	99.84	99.53	99.80	99.93	99.98	100
	Scheduled & Unscheduled	99.57	99.97	99.99	99.78	99.94	99.40	99.84	94.02	99.80	99.93	98.96	100

Table 5.2

Omega % Monthly Transmitting Time 1975

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
A NORWAY												
Unscheduled	99.97	99.96	99.99	99.98	100.00	100.00	100.00	99.96	99.96	99.99	99.97	99.94
+ Scheduled	99.97	99.96	99.99	99.98	100.00	100.00	62.83	99.96	99.98	99.99	99.97	99.94
B TRINIDAD												
Unscheduled	99.98	99.99	99.99	99.99	99.47	99.91	99.79	99.99	99.96	99.81	99.98	[illegible]
+ Scheduled	99.98	99.99	99.99	99.99	99.47	99.91	99.79	99.99	99.96	99.81	99.98	[illegible]
C HAWAII												
Unscheduled	99.83	99.97	99.92	99.90	99.80	99.99	99.86	99.65	89.89	89.97	99.88	99.93
+ Scheduled	51.86	99.97	99.92	99.90	99.80	99.99	99.59	99.65	89.89	89.97	99.88	99.93
D NORTH DAKOTA												
Unscheduled	99.94	99.82	99.93	99.97	99.97	99.85	99.96	99.97	100.00	89.84	99.93	99.91
+ Scheduled	99.87	97.43	99.95	99.97	99.97	99.95	99.96	99.97	5.83	89.84	99.93	99.91
H JAPAN												
Unscheduled					99.96	99.96	99.93	99.85	99.88	99.89	99.99	99.99
+ Scheduled					99.94	99.91	99.19	99.85	83.83	45.04	55.40	99.72

	YEARLY AVERAGE				
	NORWAY	TRINIDAD	HAWAII	NORTH DAKOTA	JAPAN
Unscheduled	99.93	99.90	99.90	99.94	99.93
+ Scheduled	86.83	99.85	95.85	91.89	87.35

5.3 OMEGA IN THE NATIONAL AIRSPACE SYSTEM

The Omega system was originally intended to provide navigation support to meet U.S. Navy ship and submarine requirements. This may have contributed to a system design which does not provide adequate coverage and achievable accuracies over CONUS. To meet the civil aviation requirements with regard to coverage and accuracy requires a reconfiguration of the system or supplementing the current system with additional transmitters or VLF communications (see Vol. III) stations. On a stand-alone basis, the Omega system is inadequate as either a primary or supplementary navigation system over CONUS. In Alaska and Alaska offshore, the Omega system is satisfactory as a VOR/DME supplement, provided VOR/DME or other navigation aids are used to provide non-precision approach capability at airports requiring this service.

Areas of concern that arise in the implementation of Omega navigation as a supplementary system are user familiarization and experience with the system and additional requirements and cost of developing procedures and facilities for using Omega in the NAS. Introduction of any new navigation system requires the development of procedures appropriate to that system followed by pilot familiarization with these procedures. Omega is no exception. However, existing avionics has been designed to operate in the NAS in a manner similar to conventional VOR/DME based RNAV. This type of avionics design minimizes pilot familiarization for current RNAV users and, to some degree, conventional VOR/DME navigation users.

As indicated, Omega does not meet the non-precision approach accuracy requirements, hence, other navigation aids are required for support during this flight phase. The impact here is one of requiring additional avionics which will affect the already crowded panel situation. Since Omega, as an enroute navigation system, cannot support non-precision approaches it is necessary that the pilot be familiar with the operational characteristics of differing navigation systems for enroute, non-precision and precision approach procedures individually.

Implementation of the Omega system as a supplement to VOR/DME in Alaska has the distinct advantage of providing RNAV capability over all of Alaska from ground level up. This capability is currently not provided. The effects of SIDs and PCAs on aircraft navigation system performance has not been fully investigated in this region. The impact of ionospheric disturbances, such as PCA's, could conceivably be significant on air travel in the remote regions of Alaska where VOR/DME coverage may be lacking. Flight testing must be performed prior to certification of Omega as a supplementary system in Alaska.

A final issue concerns that particular user travelling between Alaska and CONUS on a regular basis. Since Omega is not feasible for CONUS applications it is apparent that if Omega were to be certified as a supplement in Alaska that this particular user group would have to have avionics applicable to CONUS and avionics applicable to Alaska. If the primary navigation system in CONUS and Alaska are identical the additional avionics requirements are not as great as if the primary systems differ. Because of the Alaska/CONUS user group, consideration must be given to the overall avionics requirements.

VI. DIFFERENTIAL OMEGA SYSTEM EVALUATION

This section describes a recommended Differential Omega navigation system configuration as it relates to the navigation requirements specified in Section III. The recommended configuration is based on supportive information presented in Appendix C. Differential Omega is essentially an augmented Omega system, hence, many of the characteristics, as they relate to the requirements are similar, therefore, extensive reference is made to Section V. The section concludes with a discussion of the Differential Omega system in the National Airspace System.

6.1 DIFFERENTIAL OMEGA SYSTEM DESCRIPTION

The term Differential Omega refers to a concept for local real-time Omega accuracy enhancement to reduce potential position errors caused by propagation anomalies. In Differential Omega, a ground station at a known location measures the errors of the Omega system and transmits correction information to suitably equipped users. These users need a means of receiving and decoding the data link correction messages.

Figure 6.1 shows the operational concept of Differential Omega. The ground unit consists of a monitor receiver at a fixed, known location, and an uplink transmitter. The monitor receiver measures the actual Omega signal phases, and compares them with the nominal phase characteristics for the known monitor location. The differences between the actual and nominal phase measurements are used to generate correction data, which are uplinked to Differential Omega users in the service area. The Differential Omega receiver decodes the correction data from the uplink and uses these to correct the Omega signals measured by the user Omega equipment. For reasonable ranges, less than 200 nm [41], there exists good correlation between the Omega

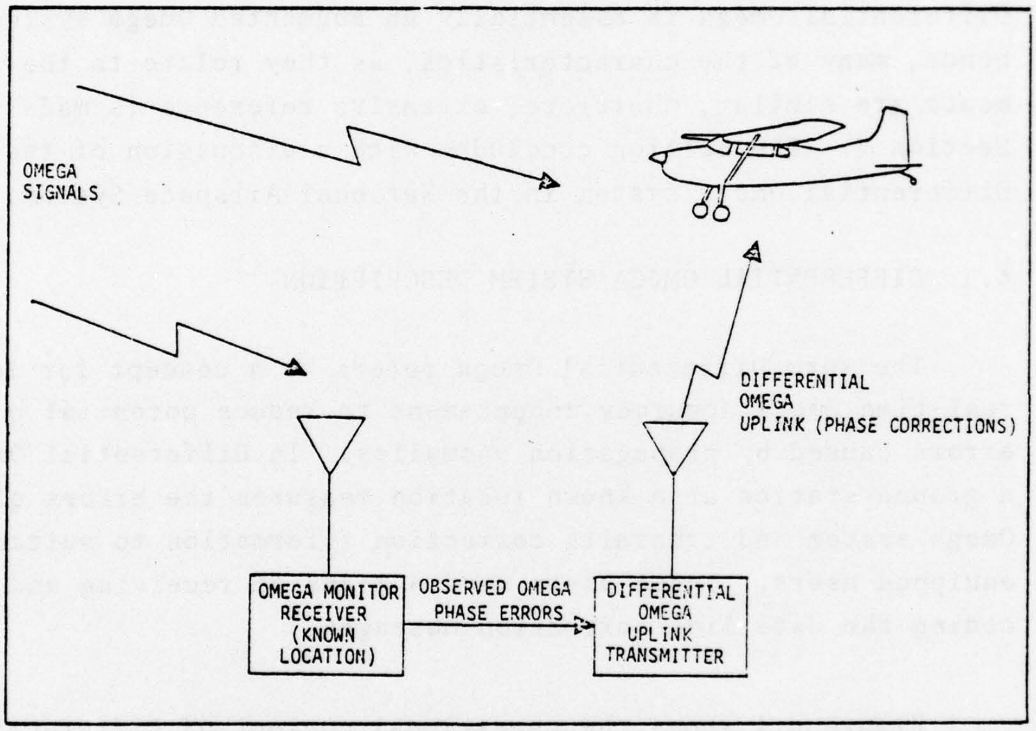


Figure 6.1 Differential Omega Concept

signal errors measured by the monitor station and by the user equipment, hence, Differential Omega can provide substantial accuracy enhancement. This accuracy enhancement is based on having reasonably good standard Omega coverage over the area of interest. Differential Omega can reduce the errors resulting from propagation phase prediction errors, but cannot correct for poor phase measurements (due to poor S/N ratios) or poor Omega station/receiver geometry.

Several different schemes are available for the implementation of the Differential Omega concept. The differences are primarily in the form of the data link from the ground monitor station to the airborne receiver. The data link elements include the content and format of the correction data to be transmitted to the aircraft, and the uplink transmission frequency (UHF, VHF, LF, for example). The alternatives available for these data link elements are discussed in more detail in Appendix C from which a good Differential Omega format appears to be the following:

- Uplink phase corrections for individual stations referenced to an atomic time standard. These atomic clocks need not be synchronized to Universal Time, as is the Omega system. However, when an economical means of time dissemination becomes available, it may be practical to synchronize the clocks at the Differential Omega stations.
- The range (largest values) of Differential Omega corrections must be determined by analysis of propagation anomalies. A first approximation is $\pm$ 2 cycles.
- The resolution of the differential correction should be less than 0.01 cycle.
- Corrections should be uplinked for all eight stations at all four Omega frequencies (10.2 kHz, 11-1/2 kHz, 13.6 kHz and 3.4 kHz).
- Corrections for each 10 second Omega commutation cycle should be uplinked.
- Predicted propagation corrections should not be incorporated into the uplink.
- The uplink medium should be VHF or LF, using existing aeronautical frequencies. A data link on a voice channel or beacon frequency is recommended.

6.2 PERFORMANCE CHARACTERISTICS

This section presents a description of Differential Omega performance characteristics and an assessment of the degree to which these characteristics meet the system requirements presented in Section III. Since standard Omega coverage over CONUS is inadequate, given that the Trinidad station goes off the air as scheduled, Differential Omega will not be considered as a candidate to meet the total CONUS requirement. An assessment of the number of Differential Omega stations needed to meet the Alaska navigation requirements, including Offshore, is made. In addition, the number of Differential Omega stations needed to serve the CONUS offshore areas where adequate standard Omega coverage is available is also estimated.

6.2.1 Coverage

There is currently no operational Differential Omega system. A number of studies and field evaluations have been conducted to determine the useful range of a Differential Omega station [43]. Adequate Differential Omega coverage requires that both differential uplink and useable Omega signals be received. In this section, Omega coverage for CONUS, CONUS Offshore, Alaska, and Alaska Offshore will be discussed, followed by a discussion of the number of Differential Omega stations required.

6.2.1.1 Omega Signal Coverage in CONUS and CONUS Off-shore. For Differential Omega to be a viable candidate for VOR/DME replacement, Differential Omega would have to supply navigational service to all of CONUS. This in turn requires adequate Omega signal coverage, with good station geometry, redundancy, and sufficiently strong signals. Because Omega is inadequate for CONUS navigation in some regions, Section 5.2.1, Differential Omega will be inadequate in those same regions, and hence inadequate for use as the primary CONUS navigation system.

Omega signals may be adequate for offshore helicopter navigation off the Georgia coast, and should be acceptable for navigation off the New England coast. In these areas, if sufficient Differential Omega uplink signal coverage is provided, Differential Omega may be a viable option to meet the low altitude Offshore requirement. Omega coverage in the Gulf of Mexico offshore area is inadequate without the Trinidad station. Therefore, Differential Omega is not a candidate for meeting the offshore navigation requirement in the Gulf of Mexico area.

6.2.1.2 <u>Differential Omega Stations needed for CONUS Off-shore.</u> The CONUS off-shore regions that have adequate Omega coverage and are, hence, considered as candidate areas for Differential Omega improvement are indicated in Figure 5.6. These regions include all of the West Coast and the East Coast North of South Carolina. Standard Omega coverage is inadequate further south along the East Coast and in the Gulf of Mexico.

A study [43] was performed to determine the number of LF stations required to provide Differential Omega coverage to meet the requirements. Locations were chosen which have listed beacons with sufficient power for greater than 300-nmi telemetering range. The power rating for the selected beacons varied from 100 W to 2 kW, with most in the 400-750 W range. The spacing of base stations has been selected to be 300 nmi or less (as determined by accuracy requirements), so that at least two stations can be monitored. Thus, the reliability advantage of redundant equipment is obtained. Under normal operation the closest station (always closer than 150 nmi) is monitored with a resulting accuracy of close to 1/4 nmi. If suitable equipment housing facilities are available, the use of redundant sites should cost only a moderate amount more than redundant equipment at a single site. The spacing is such that the required accuracies would be generally obtained even with the failure of the closest station.

The number of Differential Omega LF stations for the viable CONUS off-shore regions is six for the East Coast and six for the West Coast. Figure 6.2 indicates the East Coast stations and Figure 6.3 indicates the West Coast stations. The selected beacons are summarized in Table 6.1 which also indicates the type beacon represented.

Table 6.1
Beacon Selection

Area	Designation	Type	Remarks
West coast U.S. (6 Stations)	Neah Bay	aeronautical	
	Portland	aeronautical	
	Arcata	aeronautical	
	Farallon Island	marine	
	Los Angeles	aeronautical	
	Point Loma	time shared marine	Backup in case of failure of L.A. beacon
East coast (6 stations)	Sterns	aeronautical	
	Quonset Point	aeronautical	
	Newark	aeronautical	
	Chesapeake	marine	
	Carolina Beach	aeronautical	
	Charleston	aeronautical	

VHF Differential Omega stations are not considered feasible for the CONUS Off-shore region. The rationale is that the VHF systems are line-of-sight limited, hence, horizon cutoff must be considered. Section 3.2.3.1 specifies vertical coverage from 500 AGL and up in the off-shore enroute region. For a VHF station based landside, this translates into a reception range of only 25 nmi at 500 feet due to horizon cut-off. However, horizontal coverage must extend to 250 nmi off-shore Section 3.2.3.2. With the possible exception of mounting VHF Differential Omega stations on oil rigs, for example, this medium for the uplink is infeasible.

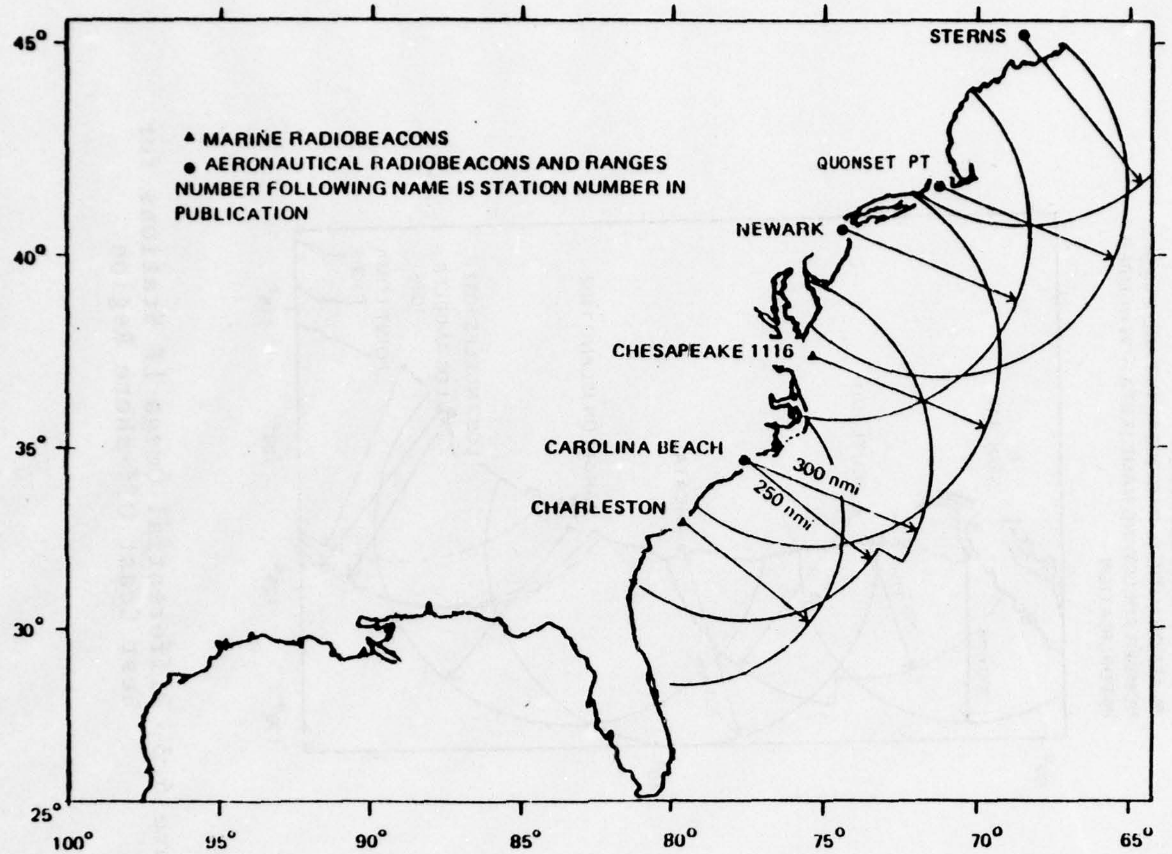


Figure 6.2 Differential Omega LF Stations for East Coast Off-shore Region

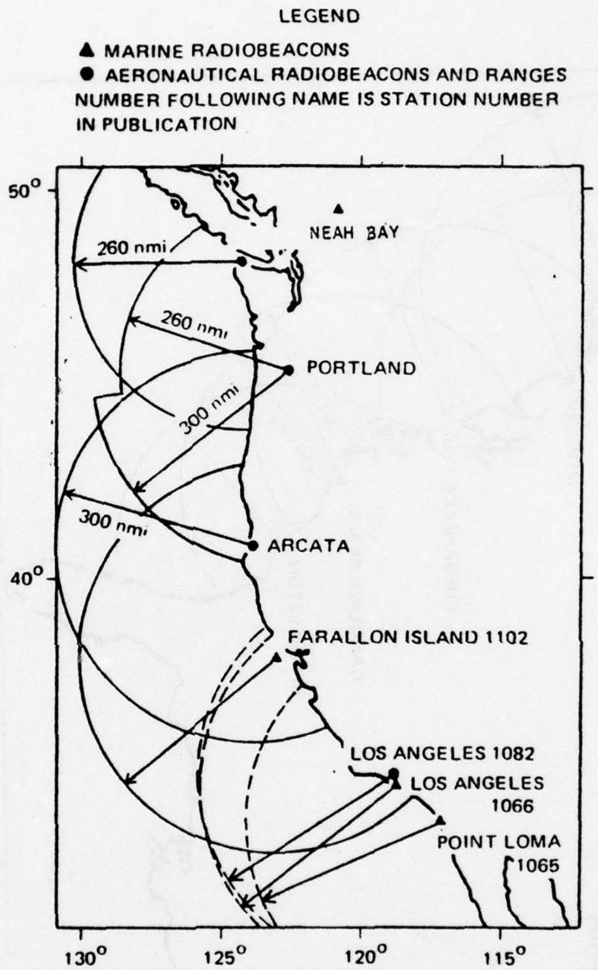


Figure 6.3 Differential Omega LF Stations for West Coast Off-shore Region

6.2.1.3 Omega Signal Coverage in Alaska. As indicated in Section 5.2.1, Alaska has the distinctive characteristic of excellent Omega coverage. Furthermore, the LOP geometries are also very favorable. Figures 6.4 indicates the predicted coverage at Noon Midsummer in Alaska and Figure 6.5 indicates the favorable geometry between LOP's corresponding to A-C and A-H LOP's. These two figures are copies of Figures 5.8 and 5.15 respectively and are shown here for reference purposes.

6.2.1.4 Differential Omega Stations Needed in Alaska. Several studies have been performed to estimate the number of Differential Omega stations required in Alaska. A study by Swanson [43] concentrated on the coastal confluence region (off-shore) and a study by Simolunas [44] considered the Alaska region exclusive of the Southeastern panhandle. Figure 6.6 shows the off-shore results and Figure 6.7 shows the Alaska coverage results. In the Alaska study a range of 150 nmi is assumed and 13 LF Differential Omega stations are found to provide single station coverage over Alaska, Figure 6.7. Expansion of the coverage radius to 300 nmi would indicate redundant coverage in a manner similar to Swanson's methodology. Combining the results of the two studies and adopting the philosophy of Swanson that the 300 nmi coverage radius provides a spacing such that the required accuracies would be generally obtained even with the failure of the closest station, yields a total number of LF Differential Omega stations for Alaska and Alaska Off-shore of eighteen (18) as shown in Figure 6.8. The five additional stations, over and above the thirteen that Simolunas proposed, primarily provide coverage in the Southeastern panhandle, the Gulf of Alaska Off-shore region and the Aleutian chain. The eighteen LF stations are presented in Table 6.2.

VHF Differential Omega stations are confronted with the same terrain limitations as the VOR system. An evaluation of the near term benefits of the Alaskan Air Navigation System [45] examined the current VOR system and assessed the requirement for additional facilities to provide the necessary navigation support in the enroute and non-precision approach flight regions. Currently,

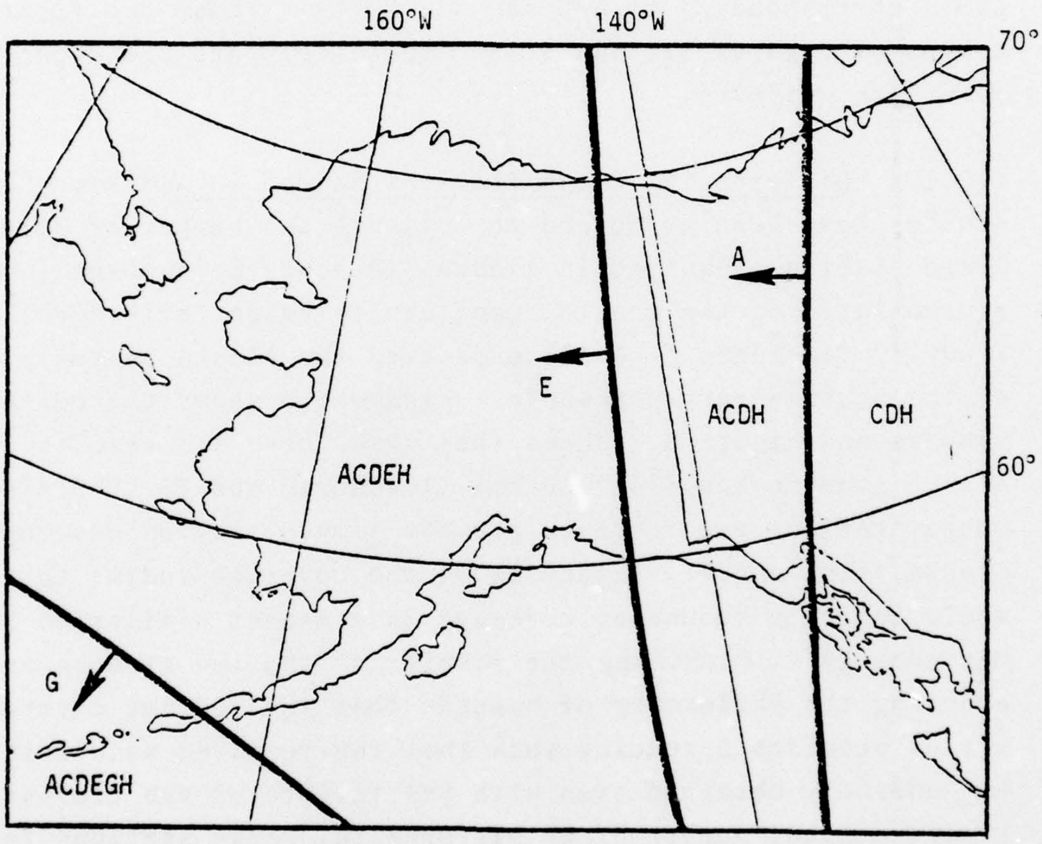


Figure 6.4 Omega Coverage Prediction for Alaska and Alaska Off-Shore at Noon Midsummer

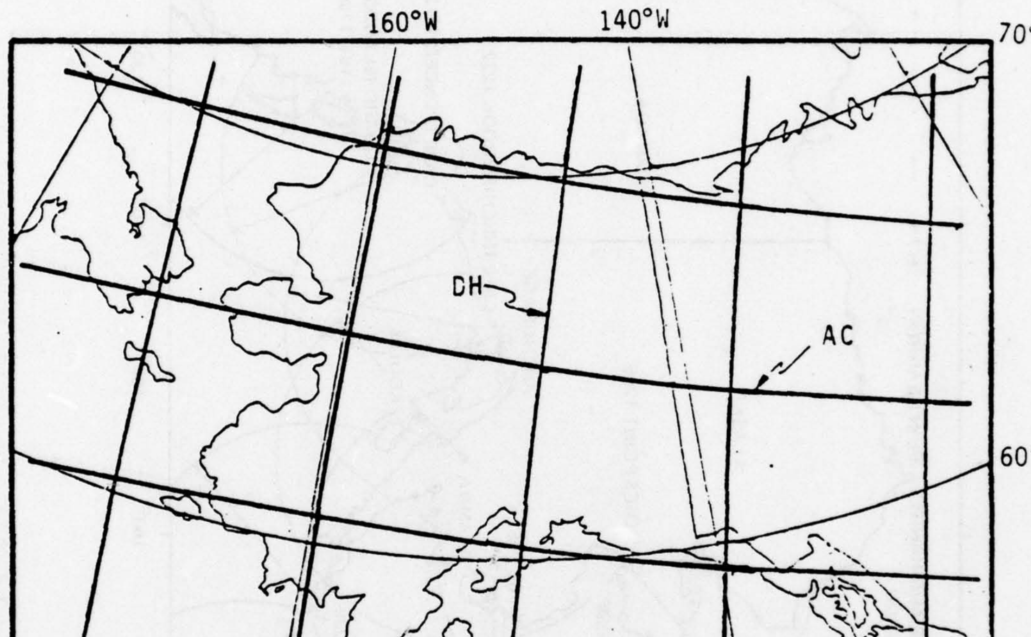


Figure 6.5 A-C and D-H LOP's in Alaska

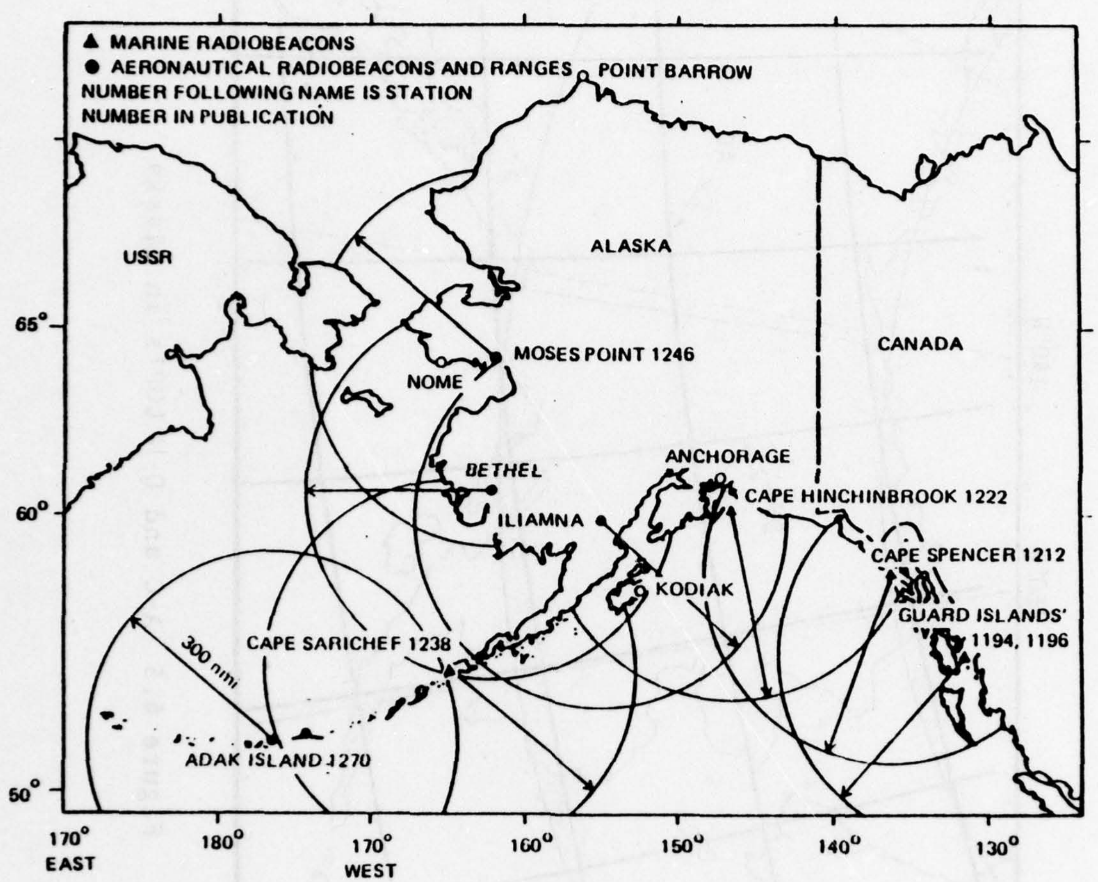


Figure 6.6 Alaska Off-shore LF Differential Omega Stations [43]

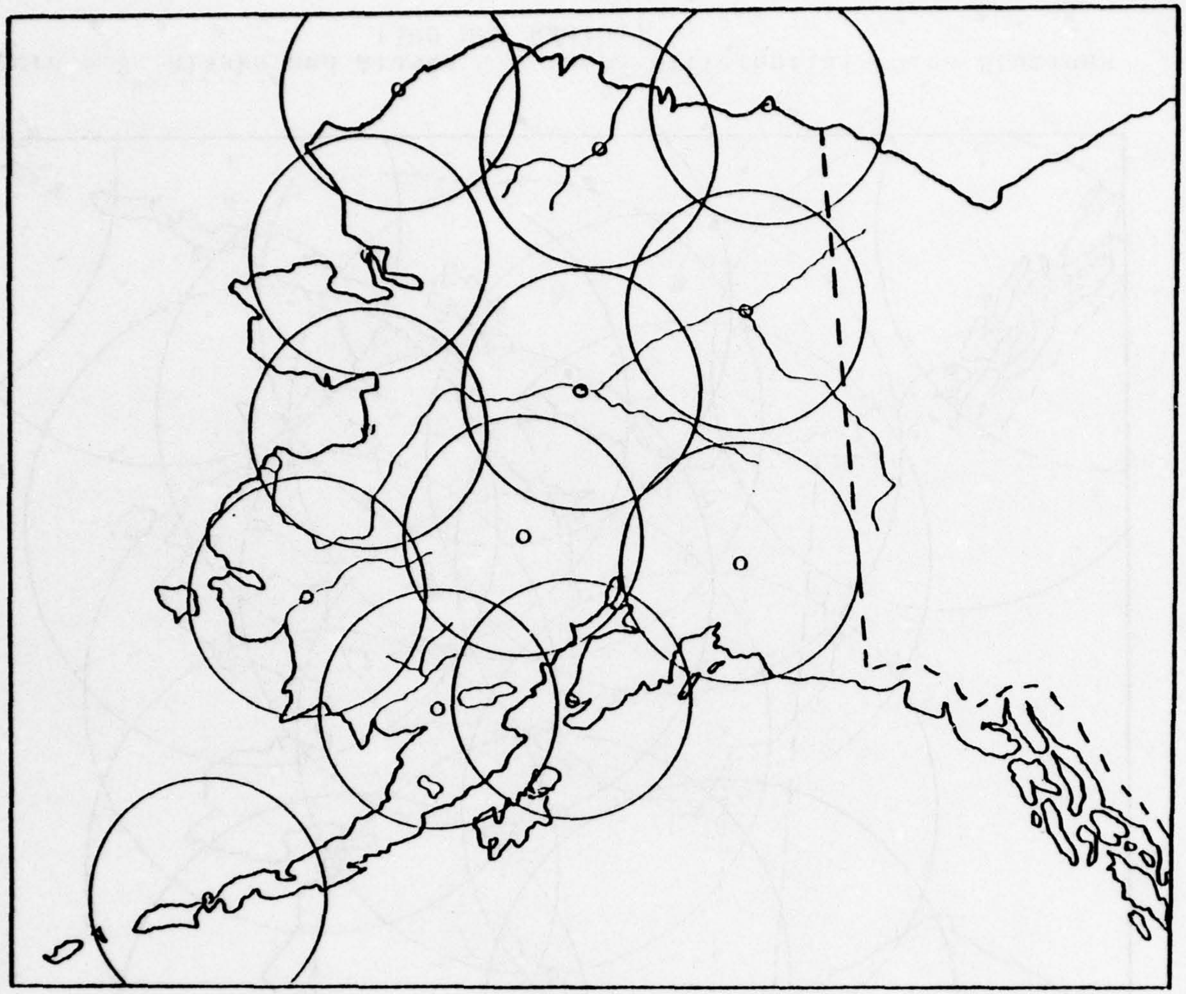


Figure 6.7 Alaska LF Differential Omega Stations [44]
(150 NMI Radius)

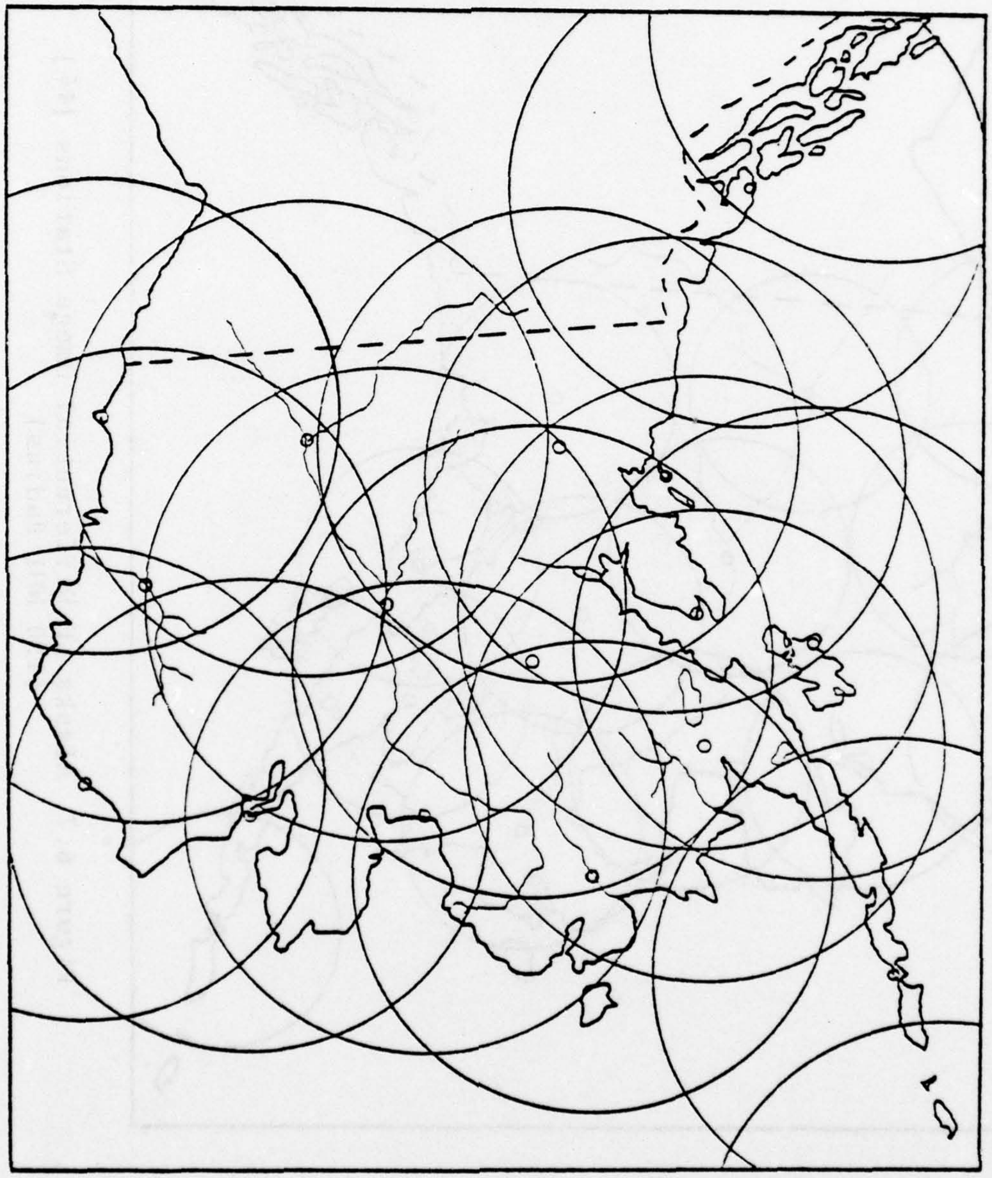


Figure 6.8 Alaska and Alaska Off-Shore Differential Omega Stations (300 NMI Radius)

Table 6.2
Alaskan Beacon Selection

DESIGNATION	TYPE
Barter Island	Aeronautical
Point Lay	Aeronautical
Umiat	Aeronautical
Kotzebue	Aeronautical
Ft. Yukon	Aeronautical
Tanana	Aeronautical
Unalakleet	Aeronautical
Bethel	Aeronautical
Farewell	Aeronautical
Gulkana	Aeronautical
Homer	Aeronautical
King Salmon	Aeronautical
Cold Bay	Aeronautical
Adak Island	Marine
Kodiak	Aeronautical
Hinchenbrook	Marine
Cape Spencer	Marine
Guard Islands	Marine

33 VOR's exist in the Alaskan region and the Alaskan Air Navigation System study indicated that an additional 38 VOR's would be needed to meet the Alaskan navigation coverage requirements. Hence, this would indicate that approximately 71 VHF Differential Omega stations would be required. However, the same horizon cutoff limitations would exist over the Alaska off-shore region as for the CONUS off-shore, hence, no attempt is made to determine the number of VHF Differential Omega stations for Off-shore.

6.2.2 Accuracy

A primary advantage of Differential Omega is its ability to correct most forms of anomalous and irregular propagation. Note, however, that Differential Omega corrects propagation anomalies, and not necessarily additive noise effects, poor LOP geometry or poor S/N ratio effects. These [39] have shown that Differential Omega accuracy varies from 0.25 nmi to 1.0 nmi RMS. These tests (performed in 1968) were conducted prior to the standard Omega system being fully operational. The addition of Omega stations since those tests would probably reduce the upper bound as signal availability is improved. Figure 6.9, taken from Reference 41, show test results of a more recent test (1977). The maximum CEP error is noted to be 0.6 nmi. It should be noted that these tests were conducted in the Gulf of Mexico region which does not have favorable standard Omega coverage or geometry (see Sections 5.2.1 and 5.2.2.1). A more optimal location for Omega signal coverage and LOP geometry is in Alaska (see Sections 5.2.1 and 5.2.2.2). The achievable Differential Omega accuracies would most likely be less, however, adequate test data does not exist for this region.

As indicated above, the Differential Omega error characteristics will vary with the specific implementation. Differential Omega should, under certain conditions, and especially in Alaska, satisfy accuracy requirements for enroute, terminal and non-precision approach. The achievable accuracy will, however, be a function of the distance between the user and the monitor. As this distance

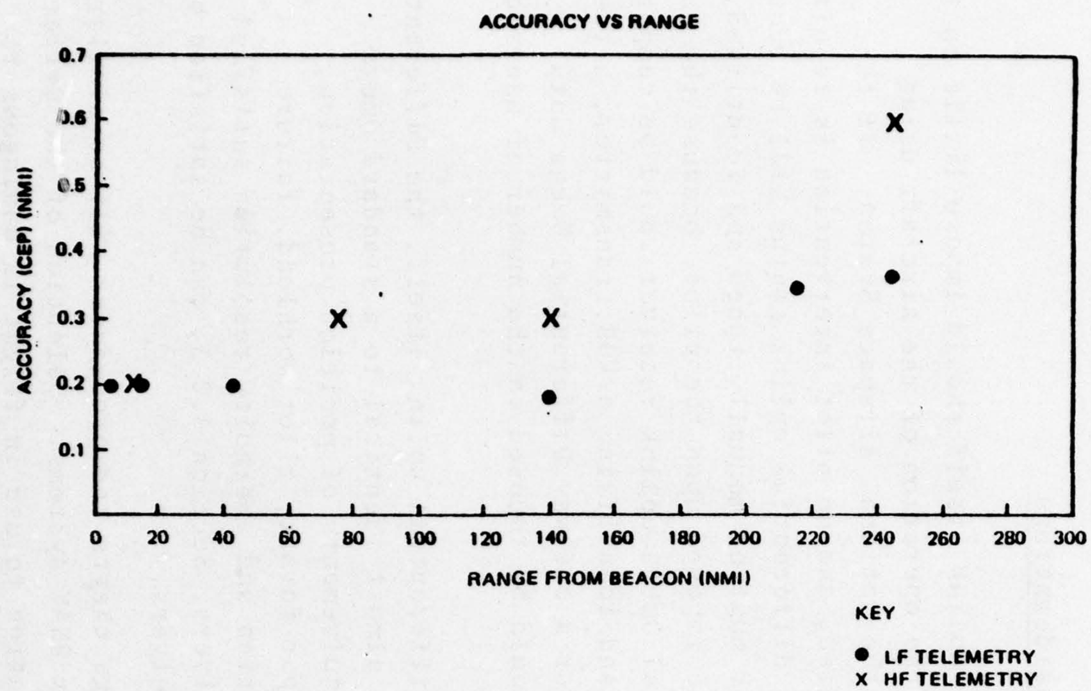


Figure 6.9 Differential Omega Accuracy versus Range from Beacon

increases the correlation between the propagation errors received by the user and by the monitor will decrease since the propagation paths will be different. Figure 6.9 displays this range dependent variation.

6.2.3 Operational Considerations

The differential uplink itself should impose little in the way of constraints on the operation of the aircraft using Differential Omega in the National Airspace System. If the uplink is fully automated, and no pilot intervention is required, only an annunciator of differential uplink status will be required. If the uplink receiever must be manually tuned and identified, little workload will be imposed upon the pilot, because the task of tuning a Differential Omega uplink receiver would be comparable to the task of tuning and identifying a VOR transmitter, a task familiar to pilots. For a one way Differential Omega data link, no constraints would be imposed on the number of users of the data link.

Aside from the differential uplink itself, the Differential Omega receiver will be almost identical to a standard Omega receiver. The same requirements of position presentation, flexibility, common input format, pilot workload, failure alerts, blunder protection and ambiguity resolution satisfied by standard Omega receivers, Section 5.2.3, can be satisfied by Differential Omega receivers.

Differential Omega charts and procedures will be similar to procedures for other RNAV systems. Selection of the Differential Omega uplink station to use in flight is analogous to selection of VORTAC stations for RNAV. Charted changeover points can be used for enroute navigation, and choice of uplink station can be specified for terminal use and non-precision approach use since, based on analysis, it would appear that the requirements can be met in these regions. Ongoing and proposed Differential Omega evaluations are designed to validate this finding.

Since Differential Omega requires an uplink system and the Omega signals, reliability should be less than standard Omega reliability and system reacquisition should be the same as Omega. Section 5.2.6 discusses Omega reliability and Section 5.2.3.6 presents system reacquisition capabilities.

Additional operational factors to be considered include transition from Omega navigation to Differential Omega navigation and the potential impact of the Differential Omega user in the same airspace with the Omega, VOR and LORAN-C user. The first factor is similar to the situation of transitioning from an enroute aid to a precision landing aid [46] in that course corrections prior to transition are being based on a lower accuracy navigation system than after transition. Transition from Omega, with accuracies on the order of 1 to 2 nmi, to Differential Omega, with accuracies on the order of .25 to .50 nmi, must be performed smoothly while making maximum use of the more accurate Differential Omega system as quickly as possible. Suitable transitioning may effect filtering schemes and/or guidance policies during transition which in turn will impact avionics costs.

The second factor mentioned above deals with compatibility between various navigation system users in the same airspace. The impact of this is compatibility in flight procedures and separation assurance. Since the Differential Omega system requires additional avionics over and above the standard Omega avionics, the implication exists that not all Omega users will have a Differential Omega capability. Special distinction between those two user groups must also be maintained.

6.3 DIFFERENTIAL OMEGA IN THE NATIONAL AIRSPACE SYSTEM

Since implementation of the Differential Omega System is dependent on the Omega system in meeting the coverage requirements, many of the comments made in Section 5.3 are applicable here. An additional advantage to be gained through implementation of Differential Omega in Alaska is that this system has the potential of providing non-precision approach capability to airports with a Differential Omega station in suitable proximity to meet the non-precision approach accuracy requirements. The full impact of the low data rate of standard Omega must be carefully considered prior to implementation. In this manner the Omega receiver can remain locked on the same station as was used enroute and acceptable accuracies achieved through use of Differential Omega corrections.

The comments made in Section 5.3 regarding additional avionics requirements and user familiarization are also applicable. These issues are somewhat more pronounced because of an additional piece of avionics required and potential additional pilot workload and familiarity with the Differential Omega avionics.

VII. VLF COMMUNICATIONS SIGNALS

This section addresses the characteristics of the VLF Communications System as they relate to the navigation requirements of Section III. This particular system is not a dedicated navigation system yet it provides adequate signals to derive navigation information. It operates essentially in a similar manner to the standard Omega system and can, in fact, operate in conjunction with it.

7.1 VLF COMMUNICATIONS SIGNALS SYSTEM DESCRIPTION

The U.S. Navy operates a VLF communication system to provide a global, all weather, highly redundant communications service to ships and submarines. In addition to the six stations operated by the U.S. Navy, there are four more stations operated by other countries. All six stations are precisely frequency and time synchronized and thus can be used for navigation purposes. Table 7.1 lists their identification, location, and frequency. High power is radiated, ranging from 100 KW to 1,000 KW, to assure high signal to noise ratios at any receiver location.

Table 7.1

VLF Communications Stations

IDENT.	LOCATION	FREQUENCY kHz
NSS	Annapolis, Maryland	21.4
NAA	Cutler, Maine	17.8
NBA	Balboa, Panama Canal Zone	24.0*
NLK	Jim Creek, Washington	18.6
NPM	Lualualei, Hawaii	23.4
NWC	Northwest Cape, Australia	22.3
GBR	Rugby, England	16.0
NDT	Yosami, Japan	17.4
JXN	Helgeland, Norway	16.4
GQD	Anthorne, England	19.0

*NBA is on standby basis

Stable signals are propagated over long distances as a result of the spherical earth-ionosphere waveguide phenomena similar to that experienced at the lower VLF frequencies of Omega (see Section 5.1). However, because of the higher frequencies, the incidence of modal interference is higher. Consequently, there are variations in the propagation velocity and attenuation caused by changes in the height and density of the ionosphere similar to that observed at the Omega frequencies. However, these variations do not present a particularly severe problem in terms of accomplishing the communications mission because of the highly redundant nature of the communications system. Also, for communications it is only necessary to track and detect changes in frequency and not phase.

Because of the use of the VLF communications signals for frequency and time reference in addition to the vital communications mission, there has been a continuing effort to improve the stability of the transmitted signals. By the application of multiple cesium beam standards for precise frequency and phase control at each station, and the synchronization of all stations to Universal Time (UT), a highly repeatable phase stable VLF radio grid covering the

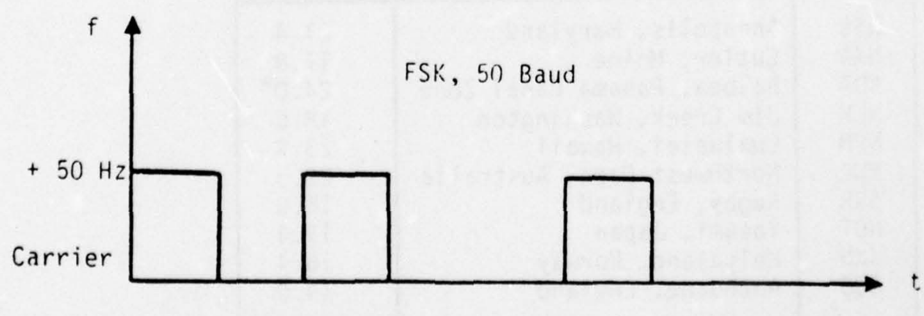


Figure 7.1 Signal Format for FSK

globe was achieved. This occurred around 1970, at which time the Omega system was smi-operational with four temporary stations. The potential application of theVLF Comm phase stable grid to navigation was recognized and a U.S. company developed an airborne navigation system based on the use of these signals. The first flight testing of the developmental set began in 1970. The sets were designed to track the phase of the carrier frequency of three or four VLF Comm stations which provided two lines-of-position (LOP's) in the radio grid network. Generally, the RF sections was designed to receive eight signals, often including Omega unique frequencies, so that the user could select the best set of three or four stations for his intended route. With the FSK signal format, as illustrated in Figure 7.1, the carrier duty cycle on the average is 50%, which with the high transmitted power provides a high average signal-to-noise ratio, making phase trac-ing relatively easy. Note that commutation is not necessary as in Omega since each station is identified by its unique frequency. The relatively easy phase tracking of the VLF Comm signals is being somewhat complicated by a change in signal format to minimum shift keying (MSK). Transition to MSK began in 1976, and all stations are expected to be modified for MSK by the end of 1978.

The MSK format is illustrated in Figure 7.2. Note that the carrier frequency is not transmitted and thus cannot be tracked. The requirement that the phase transmitted be continuous, including at the bit transition instants, causes the phase of both side tone signals to vary in time depending on the bit transition sequence. An example of the frequency and phase related to the binary input is illustrated in Figure 7.3 [47]. Note that the phase at a fixed location varies between ± 180 degrees. There are several ways to recover the apparent carrier phase. One technique is to recover the message bit format. A simpler

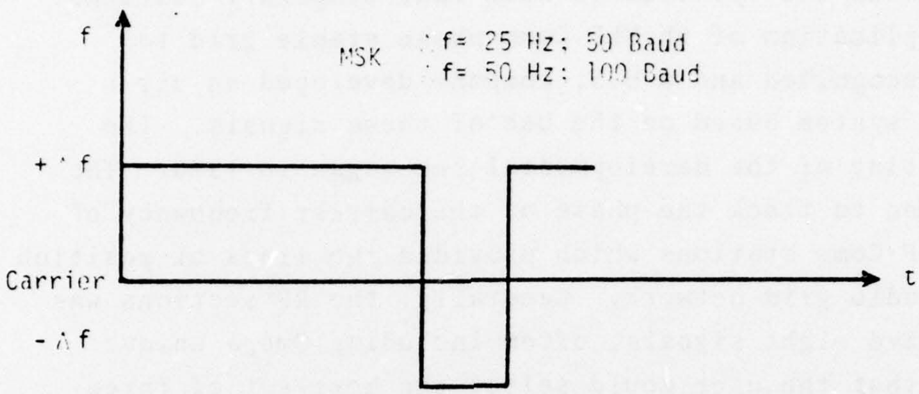


Figure 7.2 Signal Format for MSK

technique is to double either side tone frequency and track the resultant phase. Since doubling adds noise, this technique requires signal-to-noise ratios greater than unity which will usually be the case for the high power VLF Comm stations.

The following six stations are being modified to transmit MSK or MIL STD FSK. Some of these are already transmitting MSK and modificatons to the rest are to be completed by 1979:

NAA	Culter, Maine	17.8 kHz
NSS	Annapolis, Maryland	21.4 kHz
NPM	Lualualei, Hawaii	23.4 kHz
NWC	Northwest Cape, Australia	22.3 kHz
NLK	Jim Creek, Washington	18.6 kHz
NBA	Balboa, Panama Canal Zone	24.0 kHz*

* NBA is on standby basis.

The others are not under U.S. Navy control. Once modified, the stations may operate in any one of three modes listed below:

(1) MSK, ±25 Hz about the carrier at 50 baud;

(2) MSK, ±50 Hz about the carrier at 100 baud; or

(3) modified FSK, ±25 Hz about the carrier at 50 baud.

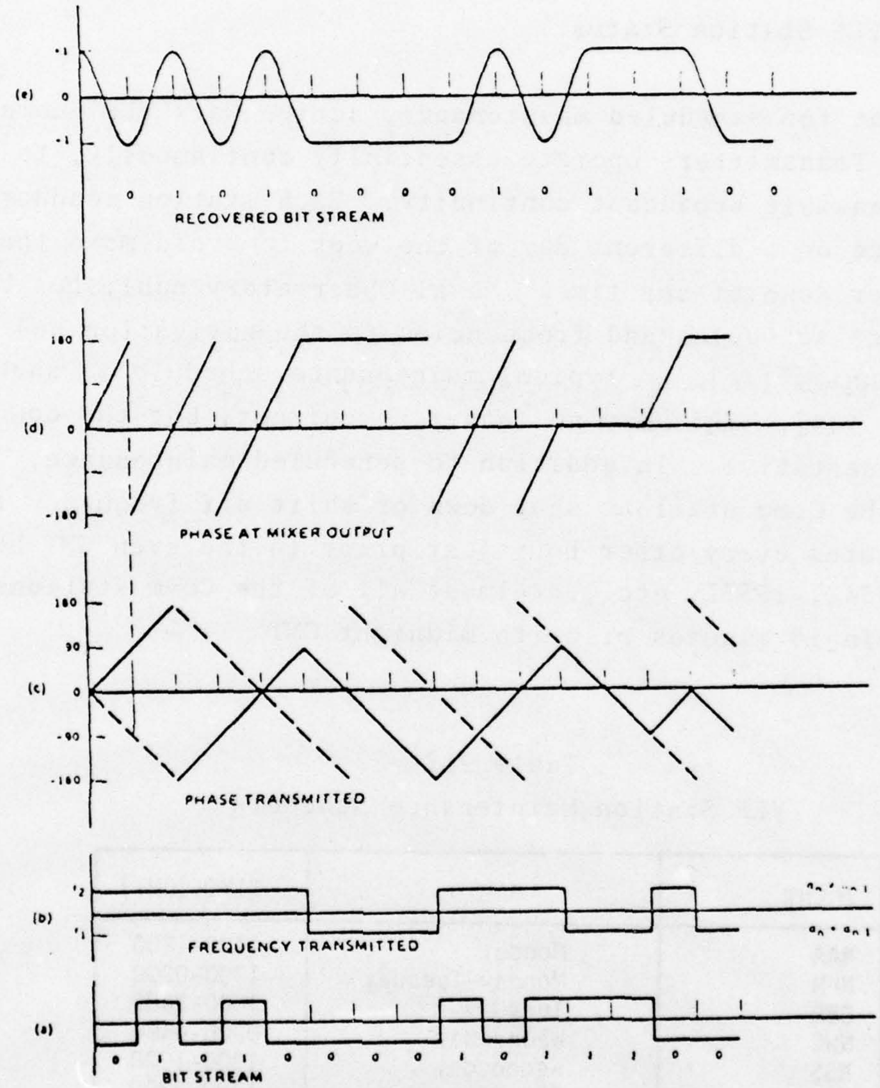


Figure 7.3 Phase Relationships (a) Bit Stream, (b) Frequency Transmitted, (c) Phase Transmitted, (d) Phase at Mixer Output, (e) Recovered Bit Stream.

The simple doubling process of recovering phase will operate on any of the three modes.

7.1.1 System Status

7.1.1.1 VLF Station Status

Except for scheduled maintenance, active Navy VLF Submarine Broadcast Transmitters operate essentially continuously, to provide maximum feasible broadcast continuity. Each station conducts maintenance on a different day of the week to avoid more than one transmitter down at any time. Naval Observatory publishes VLF maintenance schedules and frequencies to the navigation and precise time community [48]. A typical maintenance schedule is shown in Table 7.2 [49]. This may no longer be current, but the down times are representative. In addition to scheduled maintenance, some of the Comm stations shut down or shift off frequency for a few minutes every other hour just prior to the even GMT hours (e.g., 0954Z, 1557Z, etc.). Almost all of the Comm stations do this within 10 minutes prior to midnight GMT.

Table 7.2
VLF Station Maintenance Schedule

IDENT	DAY	TIME (GMT)
NAA	Monday	1400-1800
NPM	Monday-Tuesday	1700-0200
GBR	Tuesday	1000-1400
NWC	Wednesday	0000-0400
NSS	Wednesday	1300-1900
NLK	Thursday (1st & 3rd of month)	1700-2200
NDT	Daily	2300-0750
JXN	Daily	0400-0500 1000-1100 1600-1700

Reliability is defined as the percentage of time the VLF transmitters are on the air, except for unscheduled outage or casualty. The goal is 99.9 percent. The stations usually exceed 99 percent. For example the VLF at Cutler exceeded 99 percent for the past two fiscal years with 99.81 percent in FY 76.

In prior years the VLF modulation format was 50 baud FSK with a modulation index of 1.0 resulting in a space frequency of 50 Hertz above the mark or assigned frequency (ASYMMETRIC). It is planned to convert all stations to MSK and MIL-STD FSK (SYMMETRIC). MSK is similar to FSK except for a modulation index of 0.5 or one-half the data rate. For example, 200 baud MSK has a symmetrical frequency shift of 100 Hertz (plus or minus 50 Hertz from the assigned frequency). One hundred (100) baud MSK has a total frequency shift of 50 Hertz. MIL-STD FSK is centered on the assigned frequency with a modulation index of 1.0. For example, 50 baud FSK is shifted plus or minus 25 Hertz from the assigned frequency. Conversion is planned for completion in calendar year 76 for Cutler, Annapolis, Lualualei and H.E. Holt. Jim Creek and YOSAMI are planned for conversion in calendar year 78. Balboa is not planned for MSK but will be operated MIL-STD FSK as required. All other VLF stations are planned for operation at 200 baud MSK except YOSAMI and Jim Creek which are planned for 100 baud. MIL-STD FSK is a backup mode for MSK [48].

The frequency and phase of the VLF transmitters are controlled by CESIUM BEAM primary frequency standards, Hewlett Packard model 5062C (0-1695/U). The stability is plus or minus 1 part in 100 billion; accuracy is plus or minus 3 parts in 100 billion [48].

7.1.1.2 User Status

The status of the use of VLF Comm signals for navigation cannot be discussed independently of Omega for the sets in use employ various combinations of VLF Comm and Omega. The earlier sets were basically VLF Comm but could also use whatever Omega

unique frequencies were available. As the Omega stations came on the air at full power, the manufacturers began to include a capability to use the Omega navigation frequencies. Today the trend is toward a combined set using the Omega navigation signals and augmented with VLF Comm signals.

The first flight testing of a feasibility model of an airborne navigation system based on the use of VLF communications signals began in 1970. Since that time, over 1200 aircraft have been equipped with navigation sets based on VLF communication signals. The sets were produced by two U.S. companies. Prices range from $16,000 to $50,000. Application was generally found by those users operating in areas not serviced by any other radio-based navigation aid. More recently (1976-77), the manufacturers of Omega sets began offering an option to include the use of VLF Comm signals to augment Omega.

Omega has been in operational use on military aircraft since about 1970 and approximately 300 military aircraft are Omega-equipped currently. However, the number of civil aircraft currently using Omega is estimated to be less than 100, but is increasing.

A summary of distribution by user areas is shown in Table 7.3 for 1976. The avionics configurations are briefly described below:

(1) VLF COMM/OMEGA UNIQUE FREQUENCIES

This is an earlier version design which associates a specific frequency with each station to resolve station identification. Two Omega stations are currently broadcasting unique frequencies. These are Hawaii, (C), and North Dakota (D). Hawaii transmits at a unique frequency of 11.8 kHz and North Dakota transmits at a unique frequency of 13.1 kHz. The entire issue of Omega-unique frequencies is currently under consideration on an international basis.

The proposed plan is that each station transmit a single unique frequency in four time segments. Relative to the format for station A, these segments would be 4, 5, 7 and 8. The fourth navigation frequency 11.050 kHz is planned

Table 7.3

1976 VLF Comm/Omega Users

AVIONICS CONFIGURATION	TOTAL	U.S. CIVIL AIRCRAFT				NON U.S. CIVIL AIRCRAFT	
		CONUS	ALASKA	OFF-SHORE	OCEANIC	OFF-SHORE	OTHER
1. VLF COMM/OMEGA UNIQUE FREQ.	550	125	5	70		150	200
2. VLF COMM/OMEGA	600	245	20	5	100		230
3. OMEGA	37	20		1	(10)[a]		16

NOTE: a. These 10 are part of the 20 listed under CONUS

for segment 6. Based on the implications of the international frequency allocation problems, it is anticipated that unique frequencies from all stations may not become operational until 1980. Even if the Omega-unique frequencies are abandoned, this basic configuration can still operate using signals from the 10 VLF communication stations. Most sets of this basic design configuration operate in a range-range mode. A reason for this is that the phase measurements from any pair of stations cannot be simply subtracted to provide a hyperbolic grid system since each station transmits on a different frequency. Range-range mode operation requires a time reference much more accurate than can be achieved with quartz crystal oscillators. Therefore, mose of these configurations include a Rubidium atomic frequency standard.

2. VLF COMM/OMEGA

The more recent configuration is designed to process the three basic Omega navigation frequencies, 10.2 kHz, 11-1/3 kHz, and 13.6 kHz in addition to the VLF communications frequencies. A commutation operation of these three frequencies is required in the avionics in order to associate received signals with stations. The commutation operation adds some complexity to the avionics, but adds the capability to use the Omega navigation frequencies in the position fixing solution as well as for lane ambiguity resolution. There are many options available within this configuration. Clearly, a set capable of simultaneously tracking all 10 VLF communications stations, all eight Omega-unique frequencies, and all three (eventually four) Omega basic navigation frequencies from all eight Omega stations would be overly redundant anywhere over the globe. The approach used thus far has been to tailor the design for the specific area of interest. The newest of the sets currently on the market can track up to eight frequencies from VLF communication stations or unique Omega frequencies and the 10.2 kHz and 13.6 kHz Omega signals from up to all eight Omega stations.

3. OMEGA

This configuration uses Omega signals only. Most receivers available today are based on single-frequency or three-frequency implementation. The single-frequency sets generally use 10.2 kHz. The three-frequency sets track 10.2, 11-1/3, and 13.6 kHz. The means of combining the phase measurements from the three frequencies varies. A commonly used mode is the 3.4 kHz difference frequency derived from 13.6 and 10.2 kHz. Designs have been put forth which use the Omega-unique frequencies for synchronization. This technique offers a potentially lower cost design. Configurations of this type may come into use in the future if and when the unique frequencies become a permanent feature of the Omega system.

The quantities and distribution of Table 7.3 are based on discussions with the representatives of the two U.S. firms producing configuration 1 and 2 type sets. The inputs for configuration 3 (Omega), are based on discussions with Omega manufacturing company representatives of airlines.

Table 7.4 is based on an extrapolation of the current rate of production for the type 2 configuration. It is not anticipated that additional units of the type 1 configuration will be produced. The Omega quantities projected on Table 7.4 are based on the selection by the air carriers of Omega as the Loran-A replacement and that general aviation usage of Omega will gradually increase as lower cost sets becom available. Omega is estimated considerably lower than configuration 2 for CONUS because of the relatively poor Omega coverage over CONUS. In fact, all Omega estimates were tempered by the consideration of the availability of type 2 configuration sets.

In 1975, the FAA requested the U.S. Navy to assume a navigational mission responsibility for the Navy VLF stations[50]. The request was denied [51]. Since that time, a better understanding of the use of the VLF signals for navigation has been achieved by both parties. In September 1976, the Navy informed the FAA that there is no objection to the use of VLF Comm for navigation provided that the stations are not assigned additional missions as NAVAIDS, and notification procedures of the U.S. Naval Observatory are satisfactory to all concerned [49]. In addition, the FAA sponsored an FAA/DoD/Industry meeting on 14 September 1976 to discuss the use of VLF Comm for navigation purposes[52]. A preliminary proposed Omega/VLF Approval Requirement was issued and critiqued at that meeting. A revised version of the Approval Requirement was issued as a NOTAM and an Advisory Circular is in preparation. In August 1976, the FAA Western Region certified a VLF/Omega set according to AC 90-45A as an additional means of navigation for enroute use in the NAS as long as VOR/DME was also available [53].

Table 7.4

1985 VLF Comm/Omega Users

AVIONICS CONFIGURATION	TOTAL	U.S. CIVIL AIRCRAFT				NON U.S. CIVIL AIRCRAFT	
		CONUS	ALASKA	OFF-SHORE	OCEANIC	OFF-SHORE	OTHER
1. VLF COMM/OMEGA UNIQUE FREQ.	500	75	5	70		150	200
2. VLF COMM/OMEGA	3600	1500	300	400	600	150	650
3. OMEGA	1915	360	470	150	265	170	500

7.2 PERFORMANCE CHARACTERISTICS

This section presents a description of the VLF communications system performance characteristics as they relate the navigation system requirements. An assessment of the degree to which these characteristics meet these requirements is also presented.

7.2.1 Coverage

A theoretical study which assessed the availability of VLF comm. signals over North America and the North Atlantic concluded that signals from at least eight stations would be available based on signal-to-noise ratios [54]. That number is now reduced to seven since NBA, Balboa, has been taken off the air and placed on a stand-by status. Consideration of modal interference could rule out the use of VXN, Norway, and GBR, Great Britain, over Alaska and parts of CONUS at certain times during transition. In addition, geometry of LOPs must be considered. In regard to CONUS and Alaska, the two stations in Great Britain GBR and GB2, and the station in Norway, VXN provide redundant LOPs, and in effect, most of the navigation information available from the three stations is provided by any one station.

In addition, there is a minimum radius about each of the three stations located in CONUS (NLK, NAA, NSS), within which use of that station is unreliable because of modal interference. The minimum radius, which may be different for each station, is not well established, but for planning purposes, is estimated to be on the order of 300 to 600 nm.

In summary, there should be at least four VLF stations providing usable signals at any location and time over the CONUS, Alaska, and offshore areas with two to three additional stations available most of the time.

7.2.2 Accuracy

The operational accuracy of VLF Comm is quoted as being 0.5 nm CEP/hour. This number, quoted by one of the companies producing and distributing equipment of this type, is based on a large sample of operational observations [55]. There has not been any government sponsored, or independent agency, testing of the navigational accuracy based on a thorough engineering test and evaluation approach. The reason the observed accuracy is time varying is probably because of lane slippage and inadequate phase propagation corrections.

Given that adequate phase corrections are determined and applied, the accuracy of VLF comm. should be about the same as Omega. In any event, the trend in the use of VLF comm. signals for navigation is to combine the VLF comm signals with Omega signals. The average accuracy over the globe in this case should be better than Omega alone.

7.2.3 Operational Considerations

The VLF communications system, is in an operational sense, similar to the Omega system. Therefore, the discussion in Section 5.2.3 is also applicable here. It should be re-emphasized that this is not a dedicated navigation system. Hence, from an operational point of view, several factors can significantly impact its usefulness. The primary factor is loss of signal due to maintenance schedules and frequency shifting.

Pilots can generally be forewarned of such occurrences through normal channels such as the Airman's Information Manual (AIM). Because it is a Navy communication system and not a FAA owned and operated navigation system, a requirement to disperse this information does not exist.

Other operational considerations relate to an absence of a PPC type capability. This manifests itself in a time-varying accuracy as indicated in Section 7.2.2. For longer flight times the accuracy can become significant without any additional correction information. Furthermore, it is possible, when navigating with VLF communications only, that the uncorrected error can increase to the point of causing a position resolution ambiguity. Hence, the lack of PPCs causing the time-dependent accuracies need to be considered in any planned implementation of VLF communications.

VIII. NON-PRECISION APPROACH ANALYSIS

One of the requirements of a candidate enroute or terminal area navigation aid is that it also provide the capability of supporting non-precision approaches. This requirement arises from the fact that the current enroute aids (VOR and NDB) are able to provide this capability and hence any candidate system must provide at least comparable performance. Not only must the candidate system provide non-precision approach capabilities at airports currently being serviced, but also provide this capability as future non-precision approach service is required at other airports.

This section discusses non-precision (NPA) requirements in greater detail and presents the methodology employed in ascertaining the ability of the candidate navigation systems to meet the requirements. The navigation systems considered include Loran-C, VLF communications, Omega and Differential Omega. An evaluation of GPS has been purposely delayed in anticipation of further data and status. The first section presents the rationale for selecting the final non-precision approach candidate systems from the foregoing list. The method of approach is then presented followed by the presentation of results and conclusions.

8.1 NON-PRECISION APPROACH CANDIDATE NAVIGATION SYSTEMS

Currently 1541 airports in CONUS and 44 airports in Alaska have NPA procedures supported by enroute navigation aids. These airports are a subset of 14,770 airports listed on the aircraft registration tape. Beyond the criteria that the airport have a NPA procedure at least one of the following criteria must also be met in order to qualify for the subsequent - NPA analysis:

(1) Scheduled service by a CAB carrier
(2) Air taxi operations
(3) 10,000 or more annual GA operations (local and intinerant)

Whether the airport had a NPA procedure was ascertained by a review of Jeppessen approach plates [56]. Airports not meeting

the above criteria or those that have private NPA landing aids without a published procedure are not considered.

The candidate navigation systems must have suitable signal coverage to provide NPA service at these airports. As indicated in Sections 5.2.1 and 6.2.1, the Omega and, hence, Differential Omega systems do not have adequate coverage over a major portion of CONUS. Therefore these two systems, from a coverage standpoint, are not candidates to support NPA in CONUS. Thus, Loran-C is the only system considered a candidate in this region.

Another important factor in the NPA requirement is accuracy. The Loran-C accuracy, as discussed in Section 4.2.2.4, meets the non-precision approach requirement. Omega, on the other hand, does not (Section 5.2.2). It is expected that the Differential Omega should meet the accuracy requirements for NPA's (Section 6.2.2). Hence, Loran-C remains a NPA candidate in CONUS, Alaska and the off-shore regions, Differential Omega remains a NPA candidate in the Alaska, and Alaska off-shore regions and Omega is not a candidate to support NPA in any of the regions.

The VLF communications system is considered separately primarily since it is a communications system not dedicated to provide navigation signals. As discussed in Section 7.1 since it is not a dedicated navigation system it is subject to scheduled maintenance and, hence, some of the stations will experience shutdown or shift frequency for a few minutes every other hour. Therefore, the VLF communications system, on its own, does not have adequate reliability to support non-precision approaches. For this reason it is not considered as a candidate.

The candidate NPA navigation systems must not only provide service at current airports with NPA procedures but they must also provide NPA service at additional airports in the future as the need arises. The broad coverage characteristics of the systems considered is such that as the enroute regions receive

coverage over CONUS and Alaska, the terminal areas automatically receive suitable coverage. This is true except for possibly the Differential Omega system which, because of accuracy requirements (Section 5.2.1), is more severely range limited than the other VLF systems. It does not appear at this point that future NPA requirements would further eliminate any of the candidates.

In summary, the NPA candidates appear to be Loran-C in all regions of interest and Differential Omega in the Alaskan and Alaska off-shore regions. The following analysis, therefore, considers only these two systems.

8.2 METHOD OF APPROACH

The current enroute navigation aids that provide NPA service are VOR/DME, VOR, NDB/DME and NDB. Localizers also provide NPA service, however, they come under the category of a terminal approach aid and not an enroute aid. The NPA candidates are considered only as providing the same service as the enroute aids. Hence, the support provided by localizers is not considered.

Determination of the level of service provided by the current systems is achieved through an examination of the appropriate approach plates [56] which indicate the minima achievable. The published minima are determined by an application of procedures as specified in the Terminal Instrument Procedures (TERPS) document [4]. The TERPS document essentially establishes airspace criteria for safe flight operations along initial, intermediate and final approach paths. These criteria define boundaries within which no obstacle may penetrate a specified floor. Terrain and other obstructions in the terminal area, therefore, play a key role in the determination of the minima. The minima also vary for each system since the size and shape of the TERP's criteria protected airspace boundaries are dependent on the inherent system accuracies, based on navigation system errors, flight technical error (FTE) and airborne computer error.

Evaluation as to whether or not the candidate systems can meet the NPA coverage requirements is achieved by determining minima for the candidate system and comparing these with currently published minima. The NPA requirement is met at those airports where the minima are the same or decreased with implementation of the candidate system. The evaluation process is composed of two basic steps. The first involves summarizing the current minima at airports with NPA procedures and the second requires generation of new minima for the candidate systems at the same airports.

Summarizing the current minima of the 1585 airports of concern is a rather straightforward procedure. However, several groundrules were established in order to provide meaning to the NPA evaluation. First of all, rather than summarize the minima for all NPA procedures at a particular airport, only the lowest achievable minimum was noted, the rationale being that candidate navigation system must be able to at least achieve the best possible minimum achievable by the current system. In other words, the candidate system should not degrade service.
Secondly, if a particular airport has precision approaches available at all instrumented runways, the NPA procedure minima are still noted since all aircraft are not equipped for precision approaches. Finally, localizer approach is a terminal and not enroute navigation aid. If, however, a localizer approach is the only NPA available at a particular airport an attempt is made to determine if the candidate system can provide NPA service at that airport.

Generation of new minima for the candidate systems at the airports of interest requires the development of comparable TERPS criteria for these systems. By examining the magnitude of the various error components it is possible to deduce a reasonable TERPS criteria for Loran-C and Differential Omega. Advisory Circular 90-45A [8] specifies accuracy values for FTE and airborne computer as indicated in Table 8.1. For Loran-C, the navigation system error is expected to be

Table 8.1
FTE and Airborne Computer Errors [8]

• FLIGHT TECHNICAL ERROR - APPROACH = 0.5 NMI - TERMINAL = 1.0 NMI - ENROUTE = 2.0 NMI
• AIRBORNE COMPUTER ERROR - ALL REGIONS = 0.5 NMI

2000 feet to 5000 feet RMS and for Differential Omega the navigation system error is 0.25 nm (Section 6.2.2). As mentioned in Section 6.2.2 the Differential Omega accuracy will probably be a function of range from the station. Similarly, the Loran-C accuracy will have some geometry dependency. To simplify the application of the candidate system TERPS criteria it was assumed that the achievable accuracies were geometry independent. To ensure that all potential geometries would be included, the worst case navigation system errors were assumed to be representative. The disadvantage to this assumption is that the resulting TERPS criteria would be conservative. As will be observed in the final results, this disadvantage does not have a significant detrimental impact.

Combining the navigation system errors, FTE and computer error in a root-sum-squared (RSS) manner yields worst case errors of 1.1 nmi, 1.4 nmi and 2.2 nmi for the approach, terminal and enroute flight phases for Loran-C and 1.22 nmi, 1.5 nmi and 2.3 nmi for the approach, terminal and enroute flight phases for Differential Omega. Since 0.1 nmi is hardly discernable on the scales used on the approach plates or sectional charts, the Differential Omega accuracy values were used as representative of the candidate navigation systems. Under the assumption of geometry independence, the resultant TERPS criteria for the candidate navigation systems are as shown in Figure 8.1. The intermediate approach region, transition between the terminal and final approach, is assumed to have a boundary varying linearly between the terminal and final approach boundaries. The missed approach is defined as being equivalent to the current system with the exception that the expansion in the airspace boundary is bounded by the candidate navigation system enroute criteria and not the current. The obstacle clearances in each of the approach regions are consistent with the TERPS criteria for VOR with a Final Approach Fix (FAF). The obstacle clearances are 250 feet for final approach, 500 feet for intermediate approach and 1000 feet for the terminal area (initial approach).

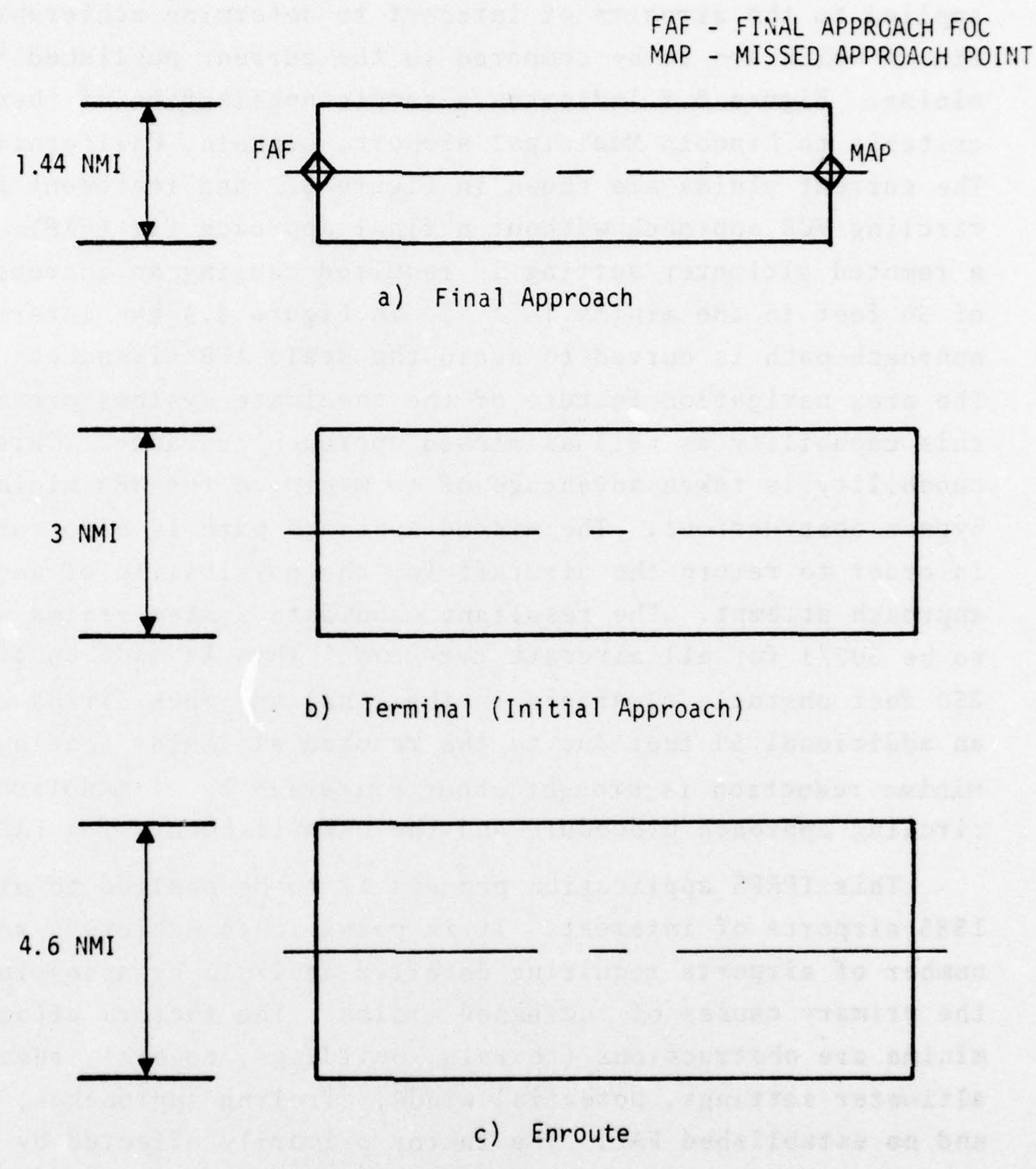


Figure 8.1 Candidate System TERPS Criteria

The candidate navigation systems TERPS criteria are now applied to the airports of interest to determine achievable minima which are to be compared to the current published NPA minima. Figure 8.2 indicates a sample application of these criteria to Lincoln Municipal airport, Lincoln, California. The current minima are shown in Figure 8.2 and represent a circling VOR approach without a final approach fix (FAF). Also a remoted altimeter setting is required causing an increase of 50 feet in the minima.[4] In Figure 8.3 the intermediate approach path is curved to avoid the Beale AFB airspace. The area navigation feature of the candidate systems provides this capability as well as missed approach guidance. This capability is taken advantage of to minimize the NPA minima to bypass obstructions. The missed approach path is also curved in order to return the aircraft for the possibility of another approach attempt. The resultant candidate system minima are computed to be 300/1 for all aircraft category. This is made up of the 250 feet obstacle clearance in the final approach airspace plus an additional 50 feet due to the remoted altimeter setting. The minima reduction is brought about primarily by elimination of the circling approach procedure and the establishment of a FAF.

This TERPS application process is to be applied to all 1585 airports of interest. It is possible to achieve a reduced number of airports requiring detailed analysis by assessing the primary causes of increased minima. The factors affecting minima are obstructions (terrain, buildings, towers), remoted altimeter settings, potential winds, circling approaches, and no established FAF. The factor primarily affected by the candidate systems is terrain, implying that the detailed TERPS application be restricted to the mountainous regions. Alaska and CONUS are therefore divided into two regions, mountainous, including the eleven western CONUS states and Alaska, and non-mountainous, the remaining CONUS states. Application of the TERPS criteria was limited to the mountainous region which includes a total of 282 airports.

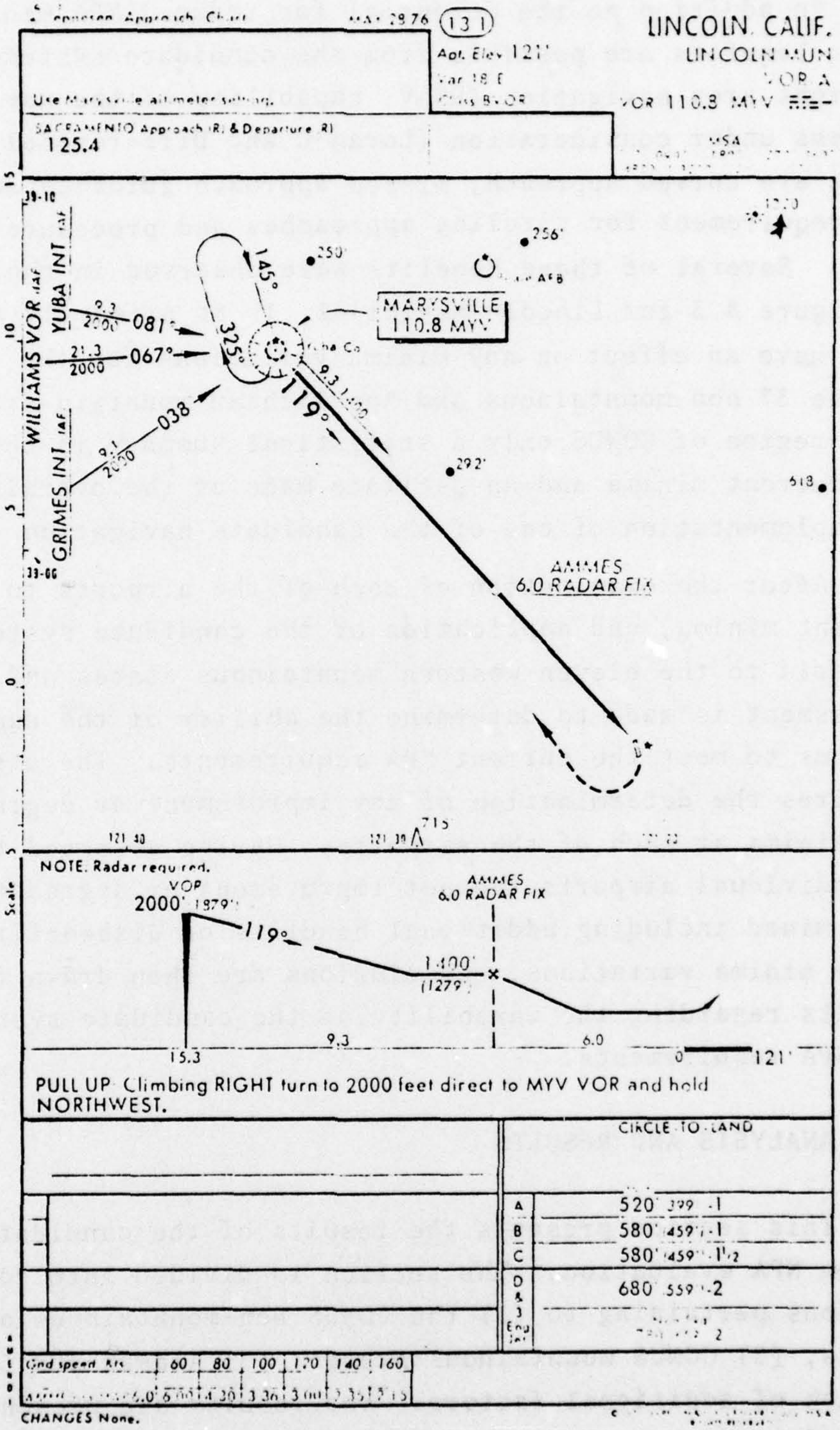


Figure 8.2 Approach Plate for Lincoln Municipal Airport, Lincoln, California

In addition to the potential for reduced NPA minima, several other benefits are possible from the candidate systems due to the inherent area navigation (RNAV) capability of the navigation systems under consideration (Loran-C and Differential Omega). These are curved approach, missed approach guidance and minimizing the requirement for circling approaches and procedure turns (inherent FAF). Several of these benefits were observed in the example shown in Figure 8.3 for Lincoln Municipal. It is primarily these benefits that have an effect on any minima variations for the 1303 airports of the 37 non-mountainous and Appalachian mountain states. For this region of CONUS only a statistical summary is obtained for the current minima and an estimate made of the overall impact of implementation of one of the candidate navigation systems.

After the examination of each of the airports to determine current minima, and application of the candidate system TERPS criteria to the eleven western mountainous states and Alaska an assessment is made to determine the ability of the candiate systems to meet the current NPA requirements. The assessment requires the determination of any improvement or degradation in the minima at each of the airports. Having assessed the impact at individual airports the net improvement or degradation is determined including additional benefits or disbenefits over and above minima variations. Conclusions are then drawn from the results regarding the capability of the candidate systems to meet the NPA requirements.

8.3 ANALYSIS AND RESULTS

This section presents the results of the candidate navigation system NPA evaluation. The section is divided into four subsections pertaining to (1) the CONUS non-mountainous and Appalachian states, (2) CONUS mountainous states, (3) Alaska and (4) a discussion of additional factors. The results are presented in the form of histograms indicating the distribution of current minima and the estimated minima for the candidate navigation systems.

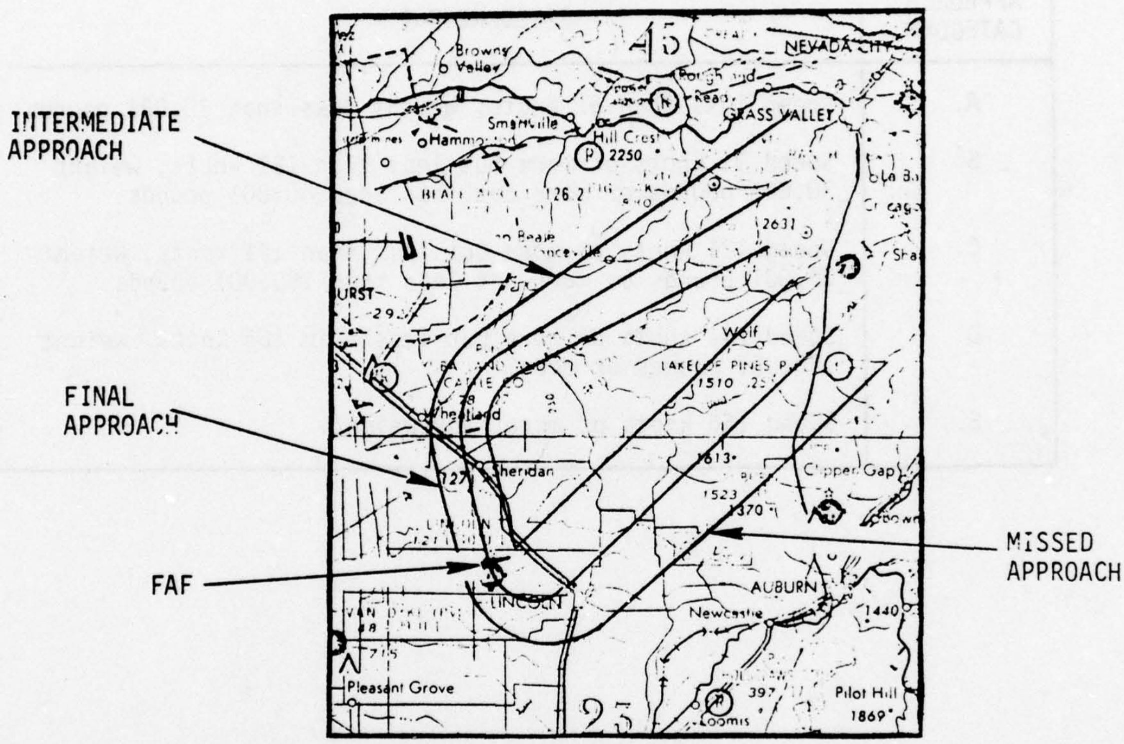


Figure 8.3 Application of Missed Approach Procedure to Sectional Chart for Lincoln Municipal

Table 8.2

Aircraft Approach Categories

APPROACH CATEGORY	SPEED/WEIGHT
A.	Speed less than 91 knots; weight less than 30,001 pounds.
B.	Speed 91 knots or more but less than 121 knots; weight 30,001 pounds or more but less than 60,001 pounds.
C.	Speed 121 knots or more but less than 141 knots; weight 60,001 pounds or more but less than 150,001 pounds.
D.	Speed 141 knots or more but less than 166 knots; weight 150,001 pounds or more.
E.	Speed 166 knots or more; any weight.

8.3.1 CONUS Non-Mountainous and Appalachian Region

As indicated previously, the CONUS non-mountainous and Appalachian region airports were examined only from the point of view of summarizing the current NPA minima. The candidate navigation system TERPS criteria were not applied since the terrain impacts are not as significant as in the eleven western states of CONUS and Alaska.

The histograms for the minima (ceilings) associated with aircraft categories A,B,C and D are shown in Figures 8.4, 8.5, 8.6 and 8.7 respectively. Aircraft categories are defined in Table 8.2. The histograms are presented in terms of number of airports with ceiling within 50-ft. increments beginning with the lowest possible ceiling for NPAs of 250 ft. Note, the peaking for all aircraft categories between 400 and 500 ft. This is attributed primarily to local obstacles such as trees, power lines and small buildings on or near the airport and to a requirement for circling approaches or to the absence of a FAF. For category D aircraft a second peak is observed between 550 and 600 ft. The cause of this is the requirement for greater airspace to accommodate the larger turning radius of category D aircraft. The increased airspace requirements arise primarily with circling approaches and curved missed approaches. In some instances the procedure turn airspace requirement has an impact. However, the procedure turn airspace requirements appeared to impact the minima in the mountainous regions more significantly than in the non-mountainous.

Table 8.2 presents a summary of the ceiling distribution for the four aircraft categories. The first column indicates the aircraft category and the second column represents the number of airports with approved minima for each category. The next column summarizes the number of airports, for that particular aircraft category, having ceiling minima less than 600 feet and the last column indicates the percentage corresponding to the airports with ceilings less than 600 feet.

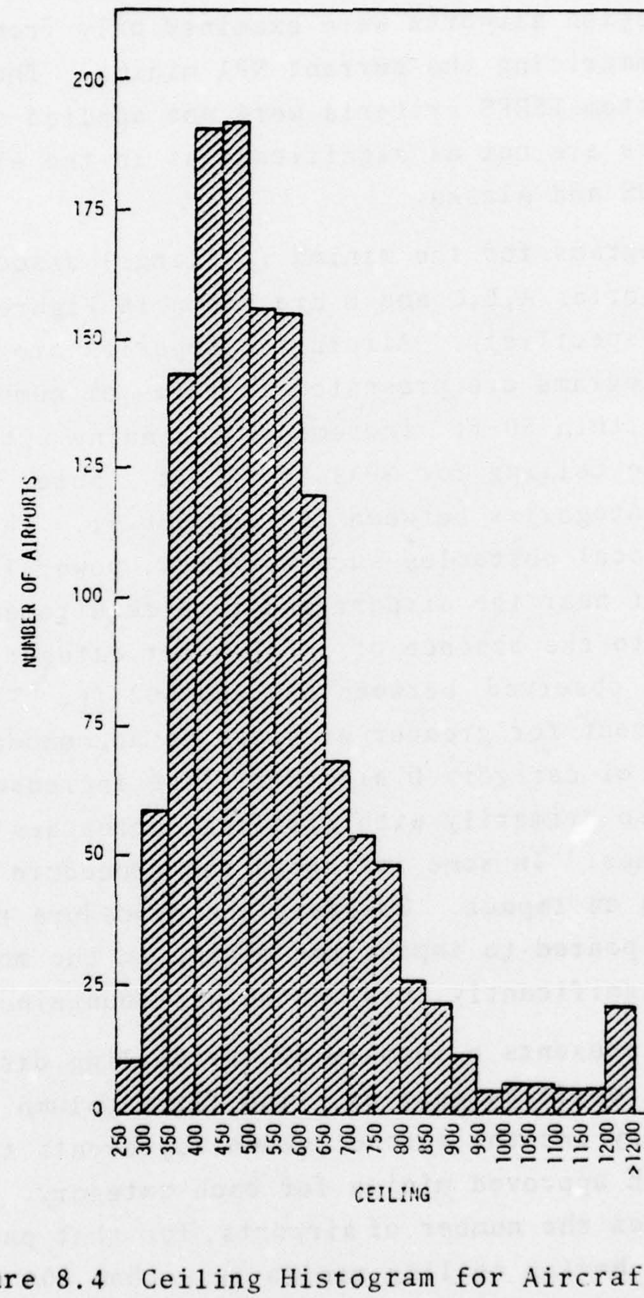


Figure 8.4 Ceiling Histogram for Aircraft Category A

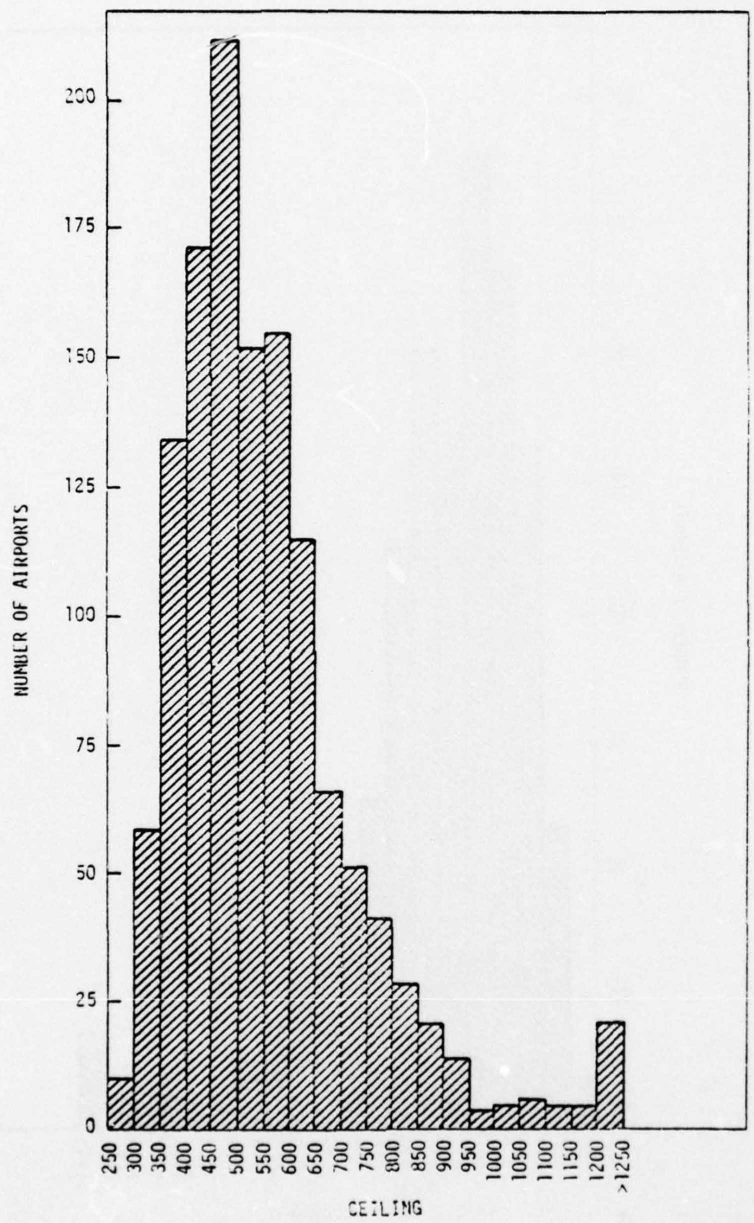


Figure 8.5 Ceiling Histogram for Aircraft Category B

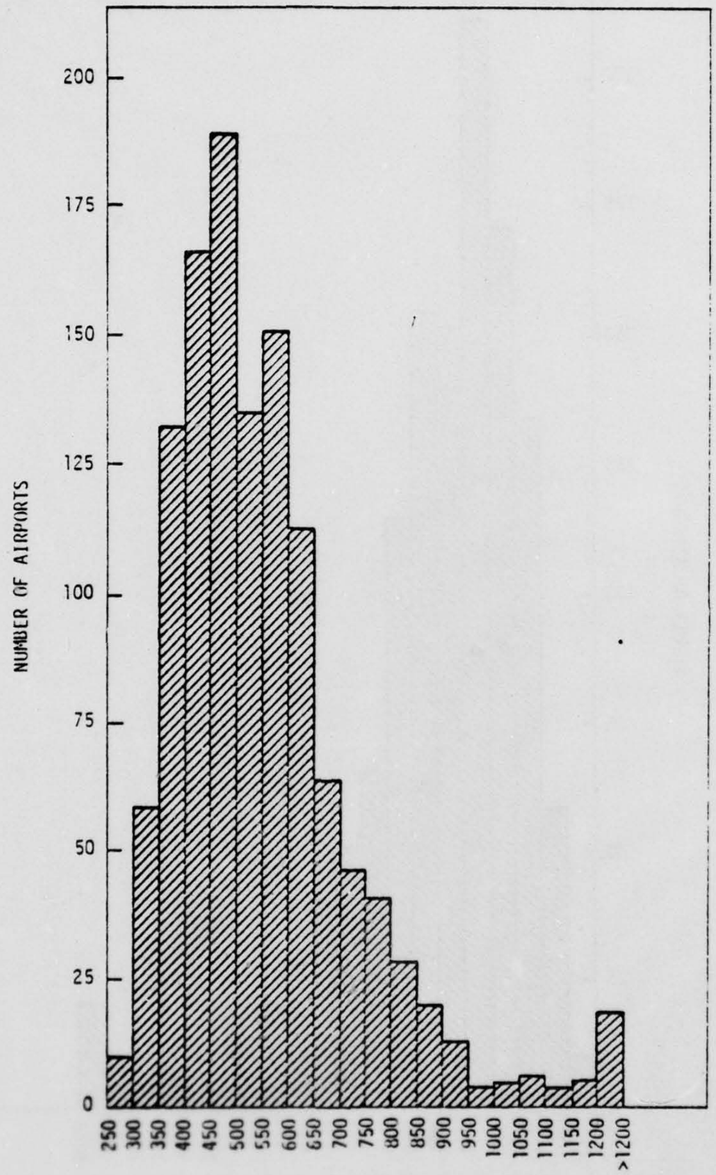


Figure 8.6 Ceiling Histogram for Aircraft Category C

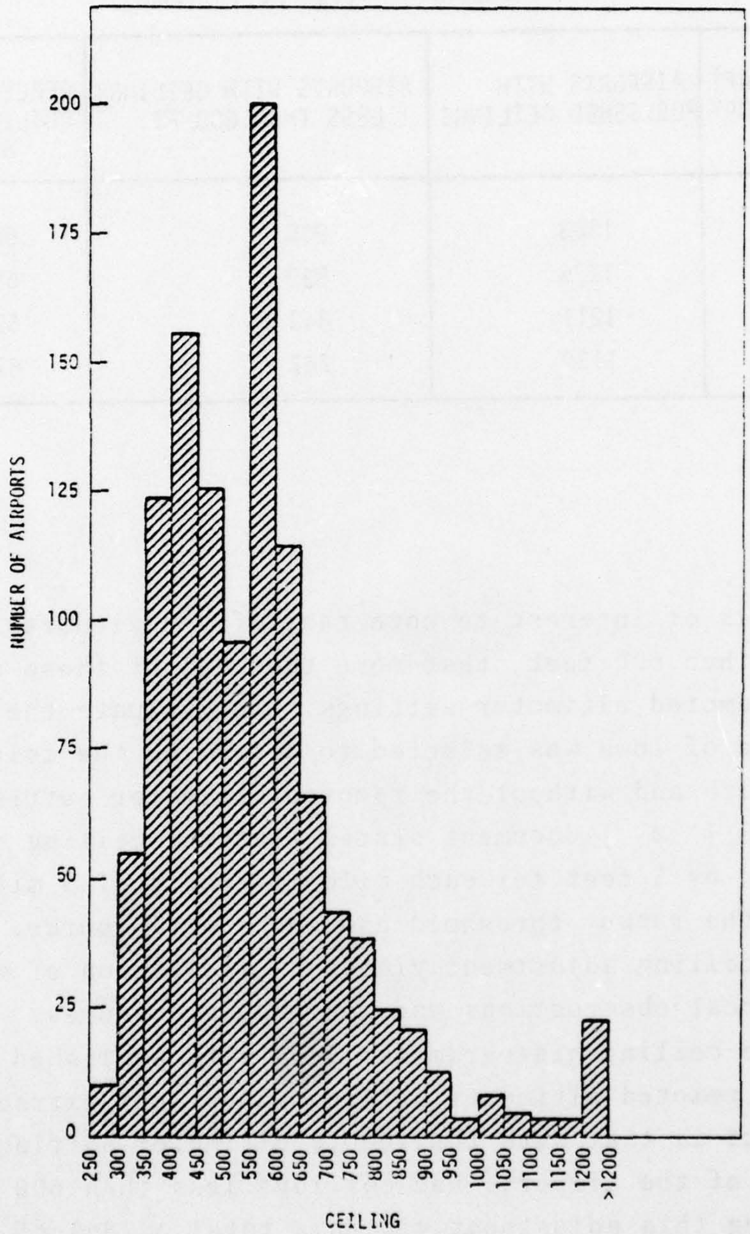


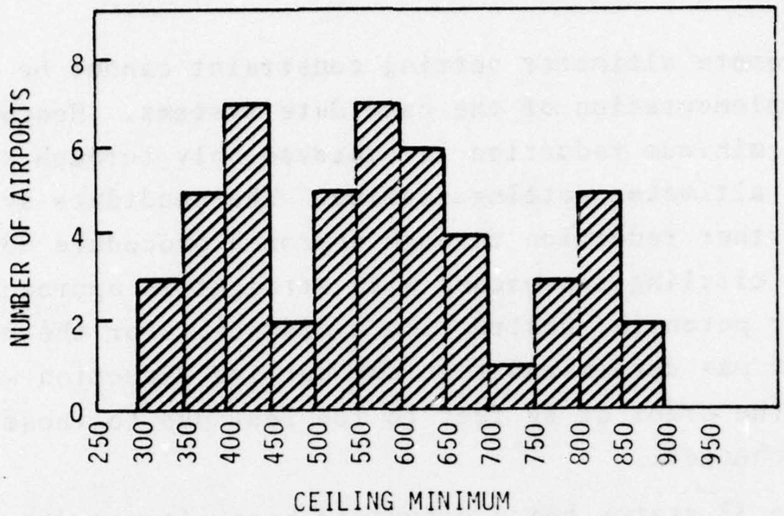
Figure 8.7 Ceiling Histogram for Aircraft Category D

Table 8.3

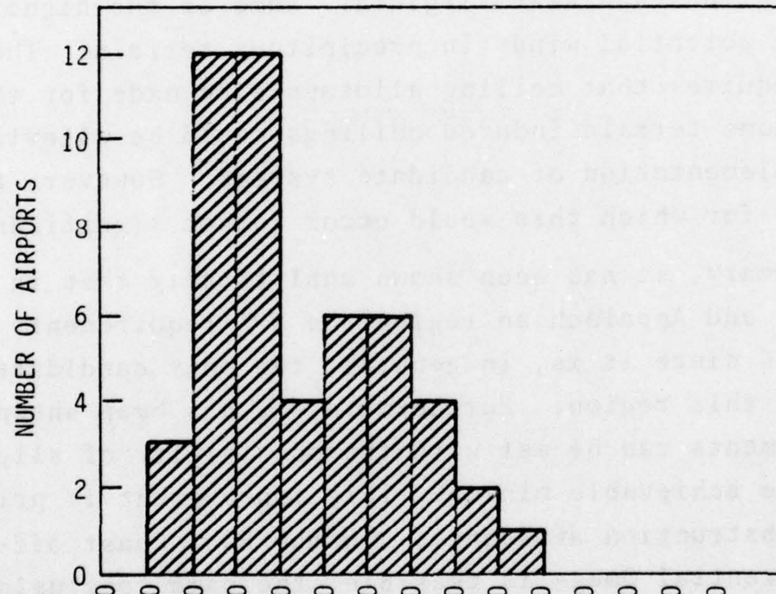
Summary Airport Minima

AIRCRAFT CATEGORY	AIRPORTS WITH PUBLISHED CEILINGS	AIRPORTS WITH CEILINGS LESS THAN 600 FT.	PERCENT AIRPORTS W/ CEILINGS LESS THAN 600 FEET
A	1303	906	69.5
B	1276	892	69.9
C	1211	843	69.6
D	1139	767	67.3

It is of interest to note that of the airports with ceilings greater than 600 feet, that more than 90% of these airports required remoted altimeter settings. To evaluate the impact of this, the state of Iowa was selected to determine the ceiling distribution with and without the remoted altimeter setting requirement. The TERPS [4] document states that the ceiling should be increased by 5 feet for each mile in excess of 5 miles distance between the runway threshold and the remote source. Extraction of this ceiling adjustment yields an indication of the ceiling due to local obstructions and approach procedures. Figure 8.8 shows the ceiling histogram for Iowa with published ceilings and with the remoted altimeter setting adjustment extracted. The net effect is that with the remote altimeter setting adjustment only 58% of the airports had ceilings less than 600 feet. Extracting this adjustment yields a total of 86% of the airports with ceilings less than 600 feet. Extrapolation to the other non-mountainous states with approaches requiring remote altimeter settings would indicate a larger percentage with ceilings less than 600 feet.



a) Published Ceiling Minima Histogram



b) Ceiling Minima Histogram with Adjustment for Remote Altimeter Setting Extracted

Figure 8.8 Ceiling Histograms for Iowa Airports

The remote altimeter setting constraint cannot be alleviated through implementation of the candidate systems. Hence, for these airports a minimum reduction is achieved only through providing additional altimeter setting service. The candidate systems may provide further reduction through approach procedure modification (replacing circling approaches with straight-in approaches, for example) or potential obstruction avoidance. For the most part, however, it was determined that any ceiling reduction would be simply on the order of 50 feet to 100 feet due to these potential procedure changes.

In the 37 states being discussed here, it was determined that less than 4% of the airports had ceiling minima greater than 1000 feet. These were primarily in the states of New Hampshire, New York, Vermont and West Virginia. Some of the higher minima result from potential winds in precipitous terrain. The TERPS document requires that ceiling allotments be made for those conditions. Some terrain induced ceilings could be alleviated through implementation of candidate systems. However, the number of airports for which this would occur is not significant.

In summary, it has been shown analytically that in the non-mountainous and Appalachian region the NPA requirements can be met with Loran-C since it is, in general, the only candidate system feasible in this region. Furthermore, it has been shown that the NPA requirements can be met with the possibility of slight improvements in the achievable minima. This improvement is primarily due to potential obstruction avoidance. In the East Coast off-shore where Differential Omega is feasible, the same conclusions apply to landside airports. With coverage to off-shore landing areas (helicopter operations to oilrigs, for example), the candidate systems would provide a NPA capability which is currently non-existent except for several certified airborne radar-assisted NPAs for oil rigs off of Jacksonville and Hyannis.

8.3.2 CONUS Mountainous

As indicated previously, the primary factor affected by application of the candidate navigation system TERPS criteria is terrain. Since terrain is a distinguishing characteristic of the eleven western states the TERPS criteria of Section 8.2 were applied to all of the airports in these states. The total number of airports examined is 238. The approach plate for each of these airports and the appropriate Sectional chart were scrutinized to determine the controlling obstacle, if any. An attempt was then made to determine the impact of applying the candidate navigation system TERPS on the minima by modifying the approach procedure according to the inherent flexibility of these systems.

Figure 8.9, 8.10, 8.11 and 8.12 represent histograms of the current NPA ceilings for aircraft Category A,B,C and D respectively, These histograms include published minima in increments of 50 feet from 250 feet to 1900 feet and then greater than 1900 feet. This is significantly greater than the histograms of the non-mountainous region which are truncated at 1200 feet. Note, in Figures 8.9 through 8.12, that the distributions contain a larger percentage of airports with ceiling minima greater than 600 feet. Table 8.4 summarizes the percentage of airports with ceiling minima less than 600 feet and those with ceiling minima greater than 1000 feet. The percentage of airports with ceilings less than 600 feet is less than for the non-mountainous region (Table 8.3). More significantly the percentage of airports with ceilings greater than 1000 feet is greater than the approximately 4% indicated for the non-mountainous region.

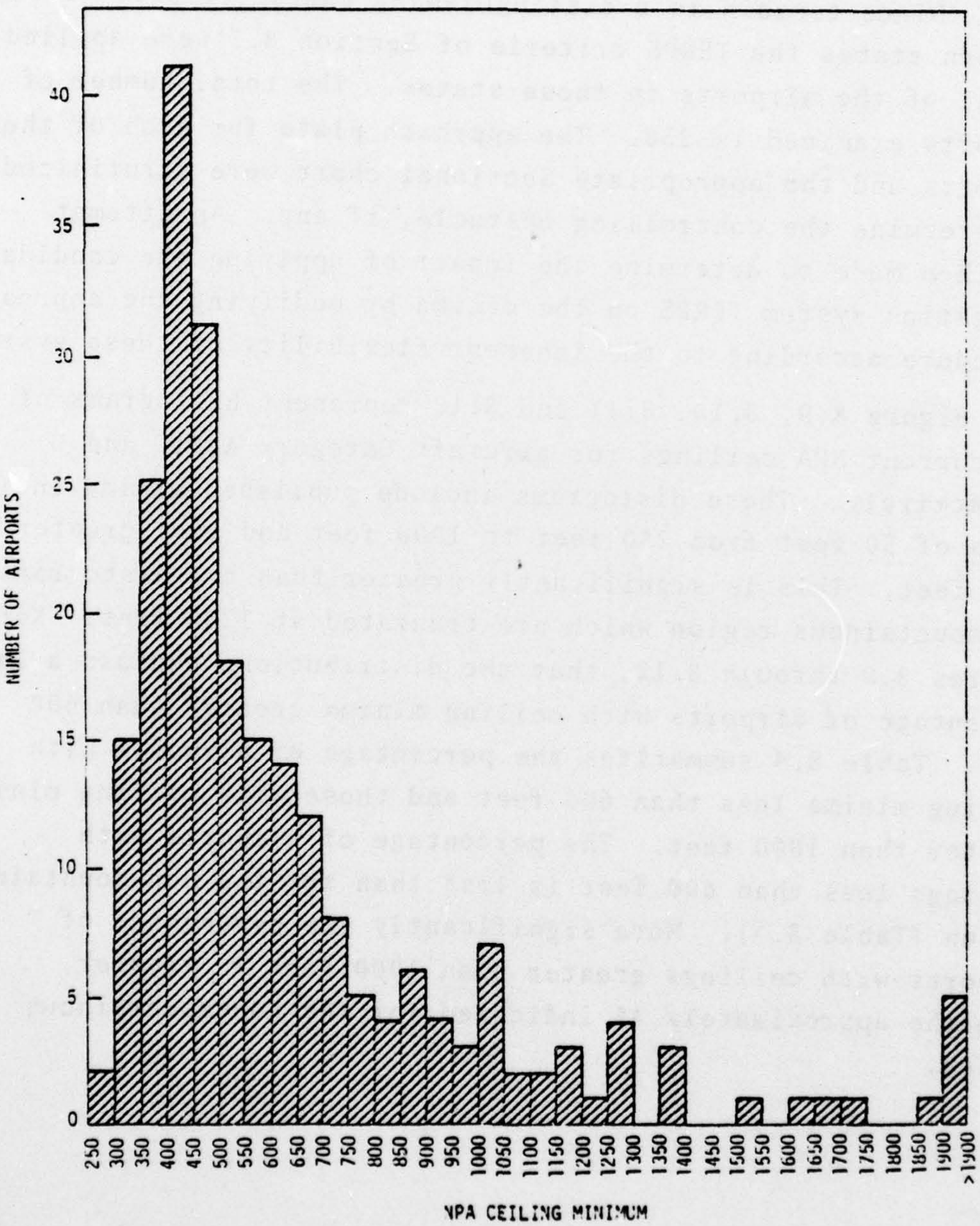


Figure 8.9 Current NPA Ceiling Minimum Histogram for Category A Aircraft in CONUS Mountainous Region

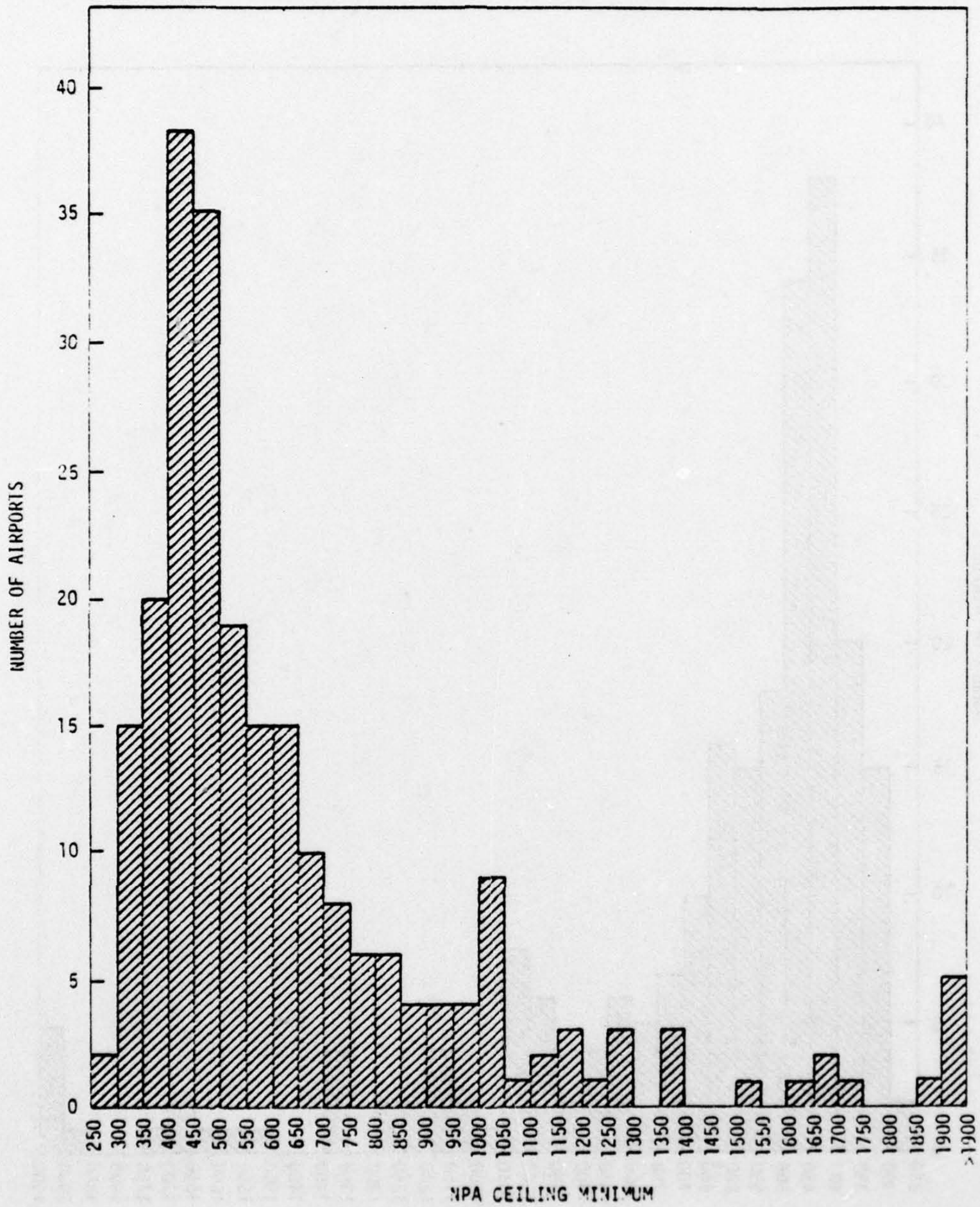


Figure 8.10 Current NPA Ceiling Minimum Histogram for Category B Aircraft in CONUS Mountainous Region

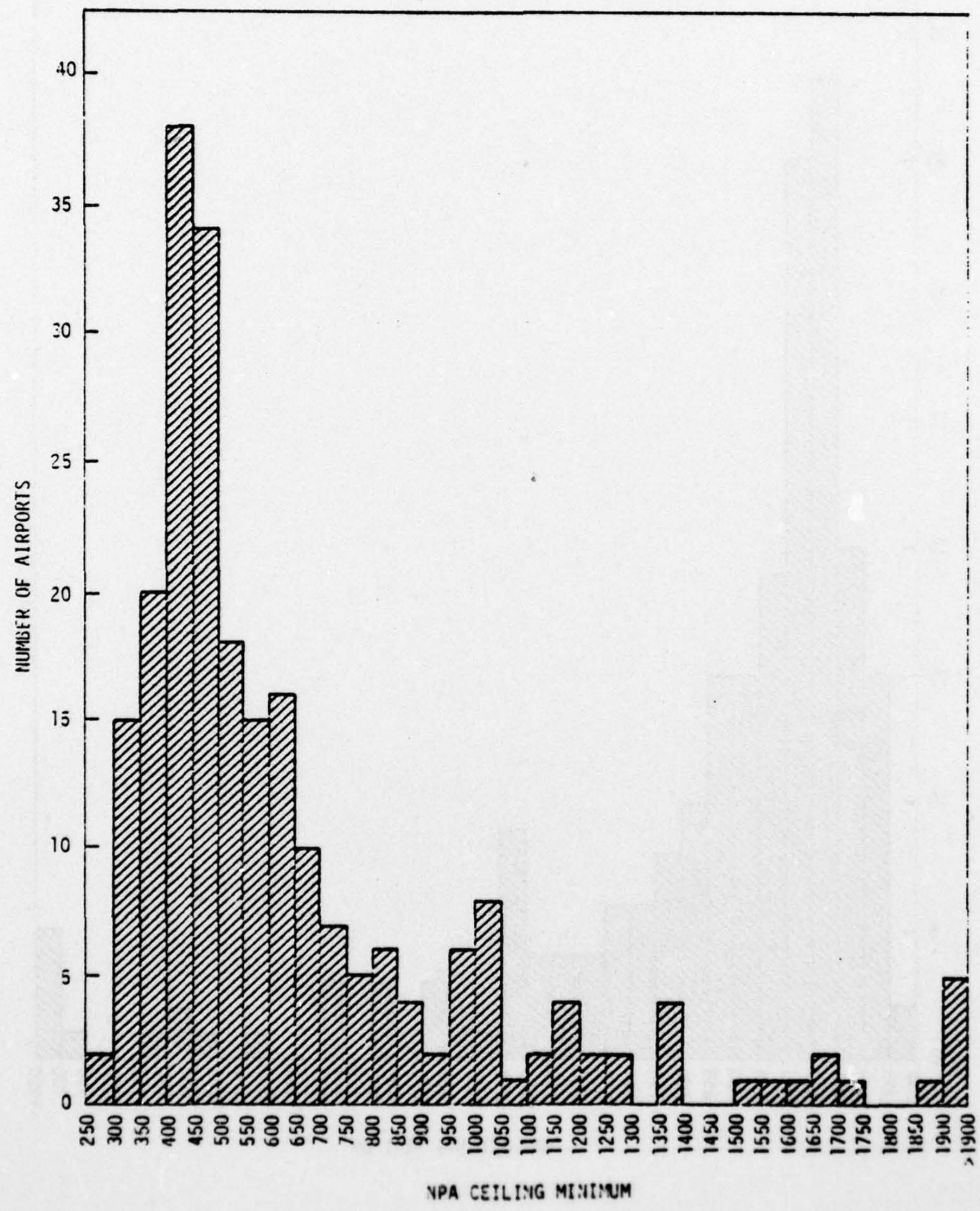


Figure 8.11 Current NPA Ceiling Minimum Histogram for Category C Aircraft in CONUS Mountainous Region

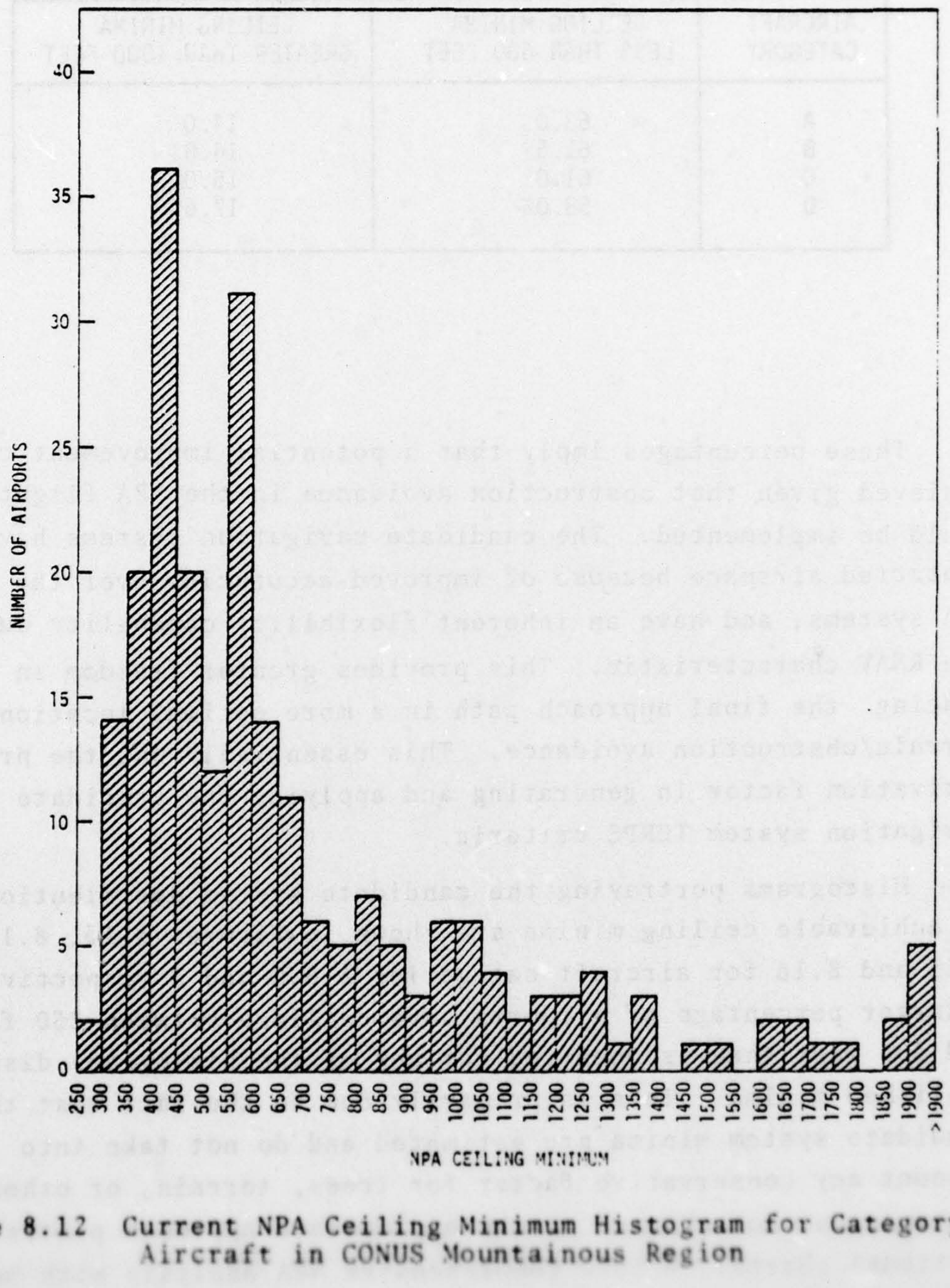


Figure 8.12 Current NPA Ceiling Minimum Histogram for Category D Aircraft in CONUS Mountainous Region

Table 8.4
Summary Airport Ceiling Minima for Mountainous CONUS

AIRCRAFT CATEGORY	CEILING MINIMA LESS THAN 600 FEET	CEILING MINIMA GREATER THAN 1000 FEET
A	63.0%	14.0%
B	61.5%	14.0%
C	61.0%	15.0%
D	58.0%	17.6%

These percentages imply that a potential improvement can be achieved given that obstruction avoidance in the NPA flight phase could be implemented. The candidate navigation systems have a smaller protected airspace because of improved accuracies over the current NPA systems, and have an inherent flexibility capability due to the RNAV characteristic. This provides greater freedom in placing the final approach path in a more optimal location for terrain/obstruction avoidance. This essentially was the primary notivation factor in generating and applying the candidate navigation system TERPS criteria.

Histograms portraying the candidate system distribution of achievable ceiling minima are shown in Figures 8.13, 8.14, 8.15 and 8.16 for aircraft categories A,B,C and D respectively. A larger percentage of airports have ceilings between 250 feet and 300 feet than is observed for any of the histograms displaying published minima. This is primarily due to the fact that the candidate system minima are estimated and do not take into account any conservative factor for trees, terrain, or other obstructions not charted on the appropriate approach plates and sectional charts. A more comprehensive NPA analysis with more detailed terrain maps and/or local knowledge of obstructions would be required for a more exacting analysis. The histograms

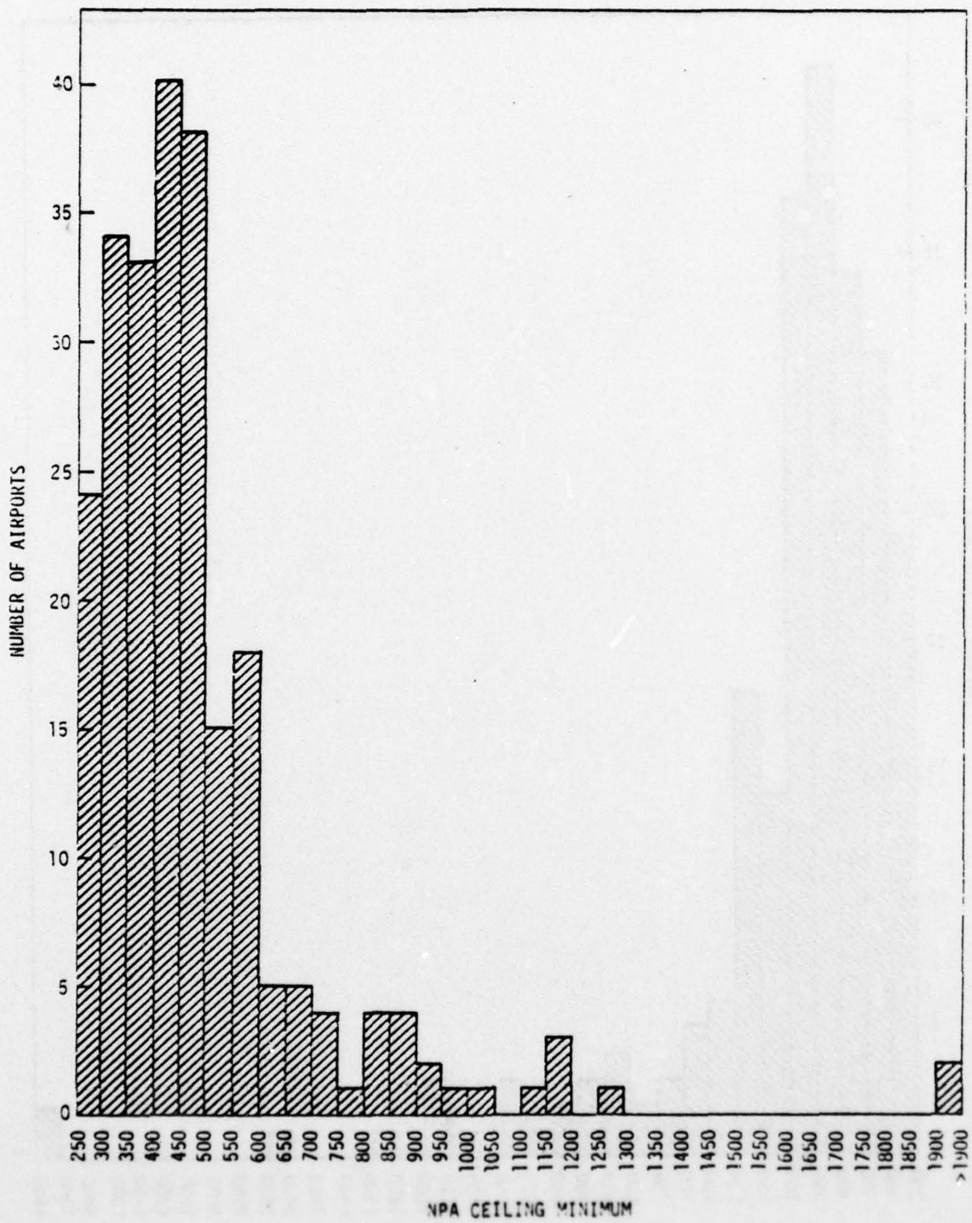


Figure 8.13 Candidate System Estimated Ceiling Minima Histogram for Category A Aircraft in CONUS Mountainous Region

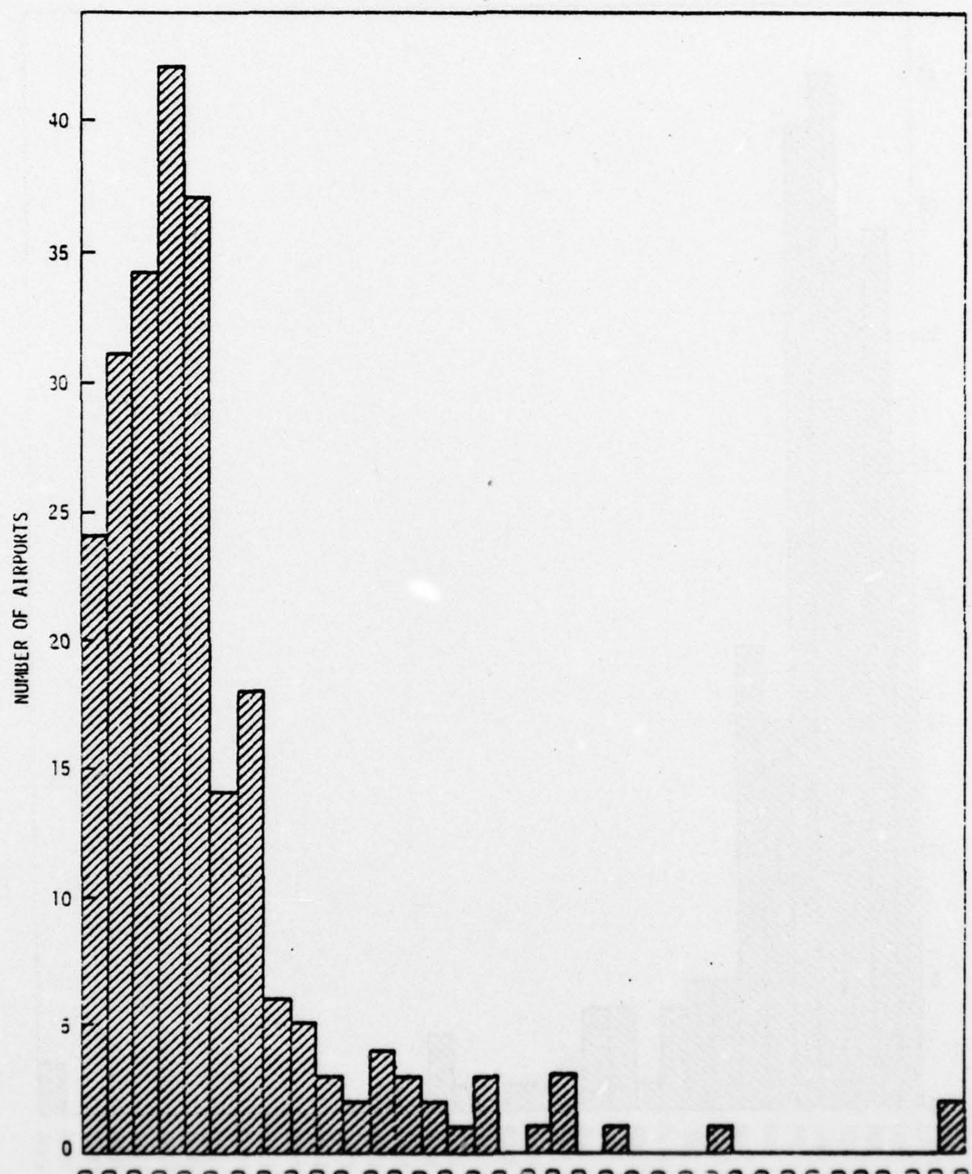


Figure 8.14 Candidate System Ceiling Estimated Minima Histogram for Category B Aircraft in CONUS Mountainous Region

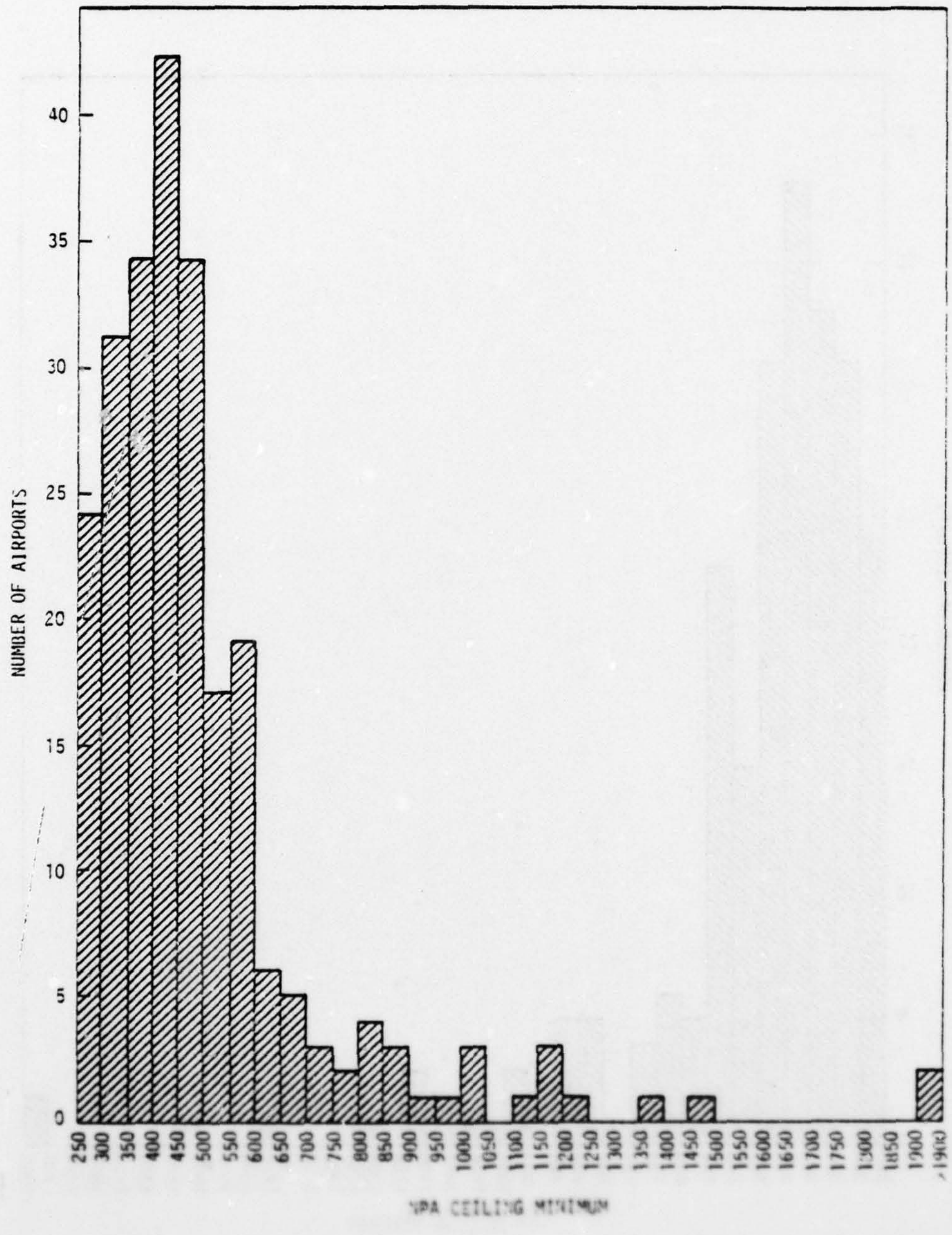


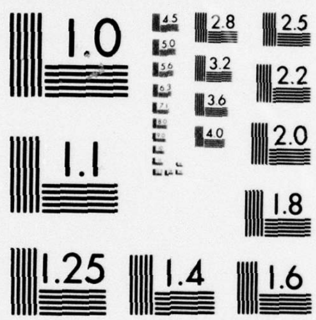
Figure 8.15 Candidate System Estimated Ceiling Minima Histogram for Category C Aircraft in CONUS Mountainous Region

AD-A056 741   SYSTEMS CONTROL INC PALO ALTO CALIF   F/G 17/7
LORAN-C, OMEGA, AND DIFFERENTIAL OMEGA APPLIED TO THE CIVIL AIR--ETC(U)
APR 78 W HEINE, F G KARKALIK, E D MCCONKEY   DOT-FA75WA-3662

UNCLASSIFIED   FAA/RD-78-30-2   NL

3 OF 3
AD
A056741

END
DATE
FILMED
9-78
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

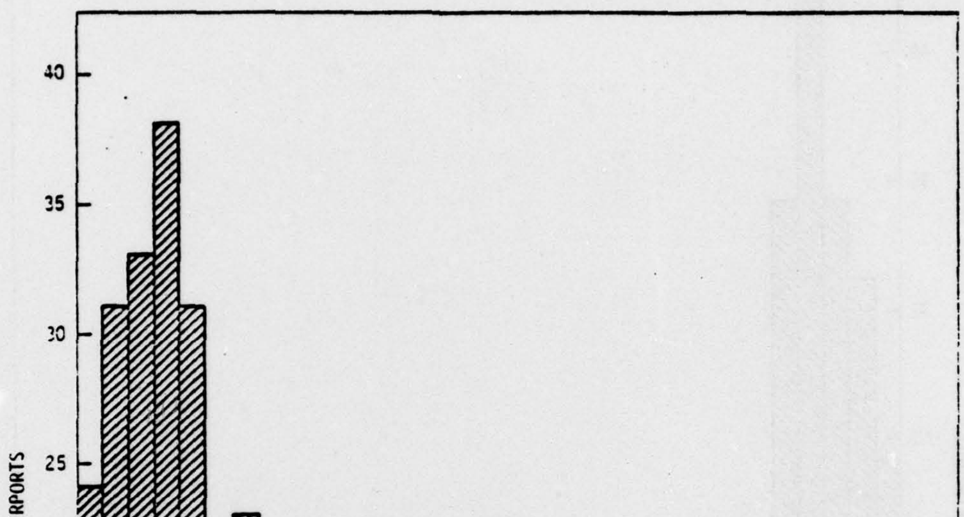


Figure 8.16 Candidate System Estimated Ceiling Minima Histogram for Category D Aircraft in CONUS Mountainous Region

are however, indicative of the types of improvements achievable through the implementation of the candidate navigation systems.

A summary of the histograms for the candidate navigation system estimated ceiling minima is given in Table 8.5 Comparison of this table with Table 8.4 indicates the estimated achievable improvement. In histogram form, the improvements appear as indicated in Figures 8.17, 8.18, 8.19 and 8.20 which indicate ceiling minima reductions for aircraft categories A,B,C and D respectively. A large portion of the improvements are 50 feet which essentially represent reduced ceilings due to implementation of a FAF or elimination of a circling approach. However, it is of interest to note that more than one third of all the 238 airports examined displayed ceiling minima reduction greater than 50 feet. (36.1% for aircraft category A, 37.8% for aircraft category B and 38.7% for aircraft categories C and D).

Thus far the discussion regarding improved minima has only considered the ceiling and not the visibility. The reason for this is that the TERPS airspace criteria determine the ceiling and other criteria determine the resulting visibility. Table 8.6 is a reproduction of Table 6 in the TERPS document that shows the relationship between ceiling and visibility. From this table the observation can be made that a suitable ceiling reduction will potentially result in a visibility reduction. Hence, ceiling improvement implies a potential visibility improvement but never a visibility degradation.

Table 8.5
Summary Results of Candidate System Estimated Ceilings

AIRCRAFT CATEGORY	ESTIMATED CEILING LESS THAN 600 FEET	ESTIMATED CEILING GREATER THAN 1000 FEET
A	85.0%	3.4%
B	84.5%	4.6%
C	84.0%	5.0%
D	80.0%	5.0%

Table 8.6

Effect of HAT/HAA and Facility Distance on Visibility Minimums [4]

VOR - TACAN - LOC - LDA - ASR - NDB - LFR - DF							
*HAT/HAA (FT)	250-500	501-625	626-750	751-875		876-1000	Over 1000
DIST. (NM)	0-10	Over 10-15	Over 15-20	Over 20-25	Over 25-30		
Cat. A	1	1	1	1	1	1-1/4	Increase the visibility by 1/4 (not to exceed 2 Mi) for each added 125 ft of Ht above TDZ (Par. 330.c.)
B	1	1	1	1-1/4	1-1/4	1-1/2	
C	1	1	1-1/4	1-1/2	1-1/2	1-3/4	
D	1	1-1/4	1-1/2	1-3/4	2	2	
E	1	1-1/4	1-1/2	1-3/4	2	2	

NOTE: NDB, LFR, & DF Appr. N/A over 15 Miles, ASR Appr. N/A over 20 Miles. For ASR, NDB, LFR, & DF dist. over 10 mi. apply 25-30 column.

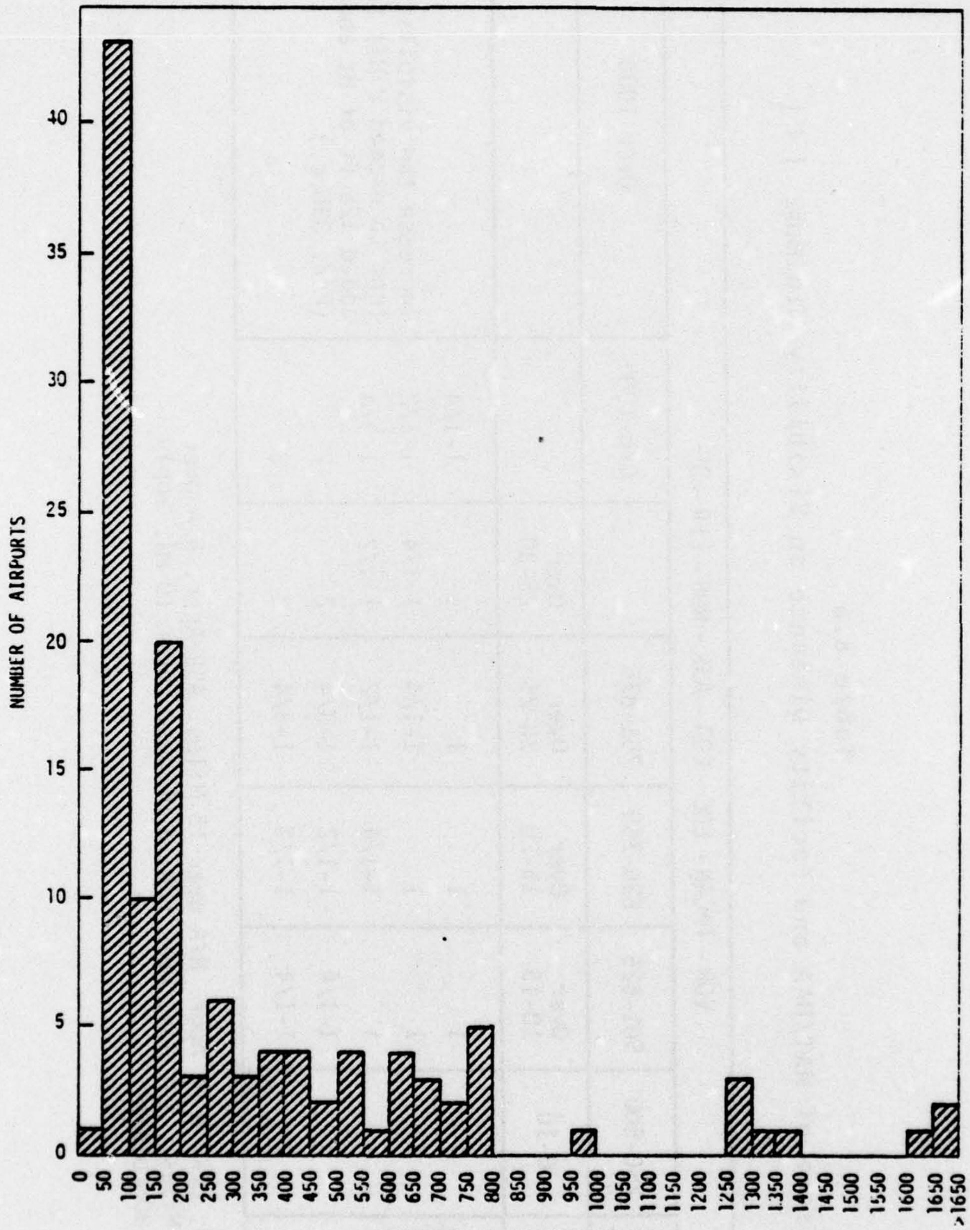


Figure 8.17 Histogram of Ceiling Minima Reduction for Aircraft Category A

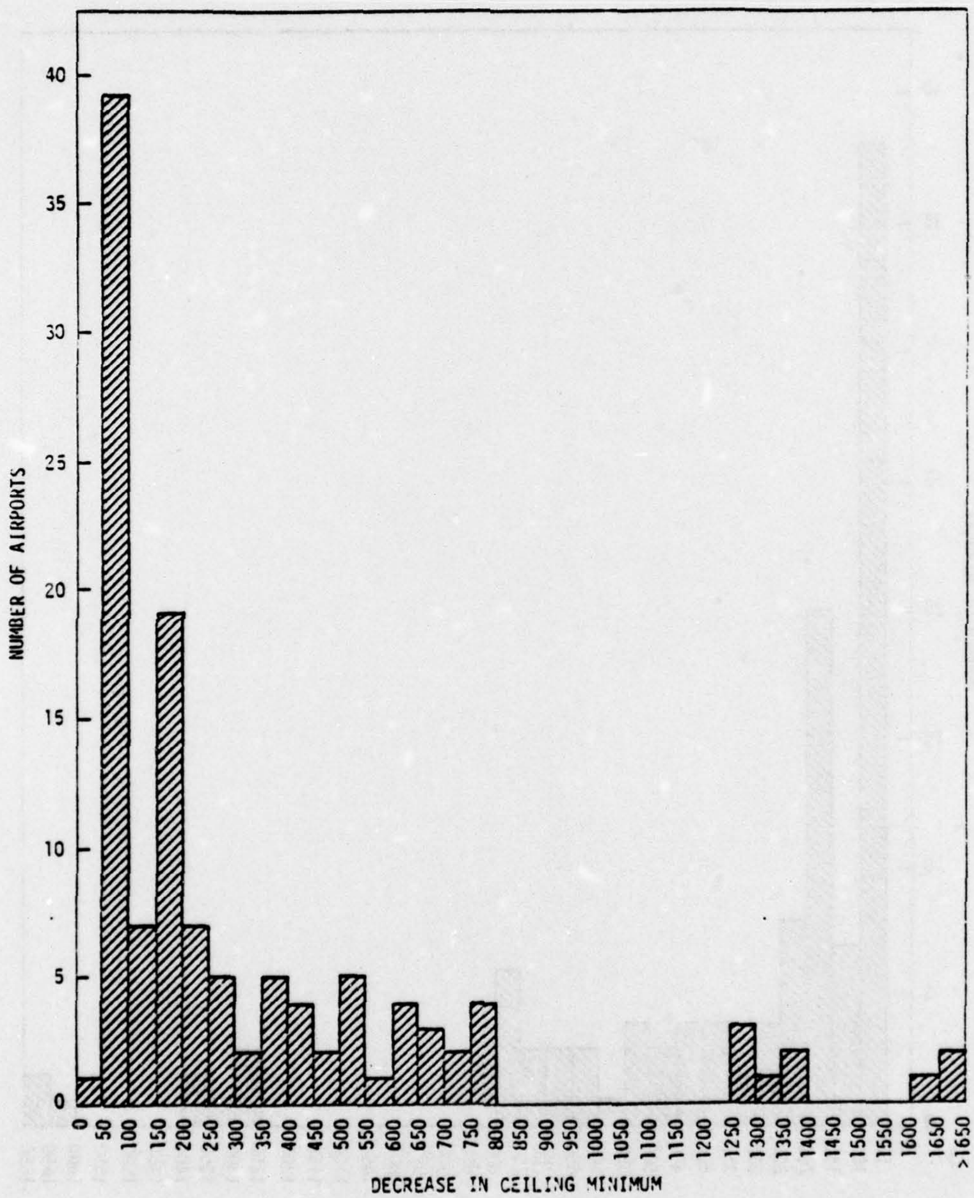


Figure 8.18 Histogram of Ceiling Minima Reduction for Aircraft Category B

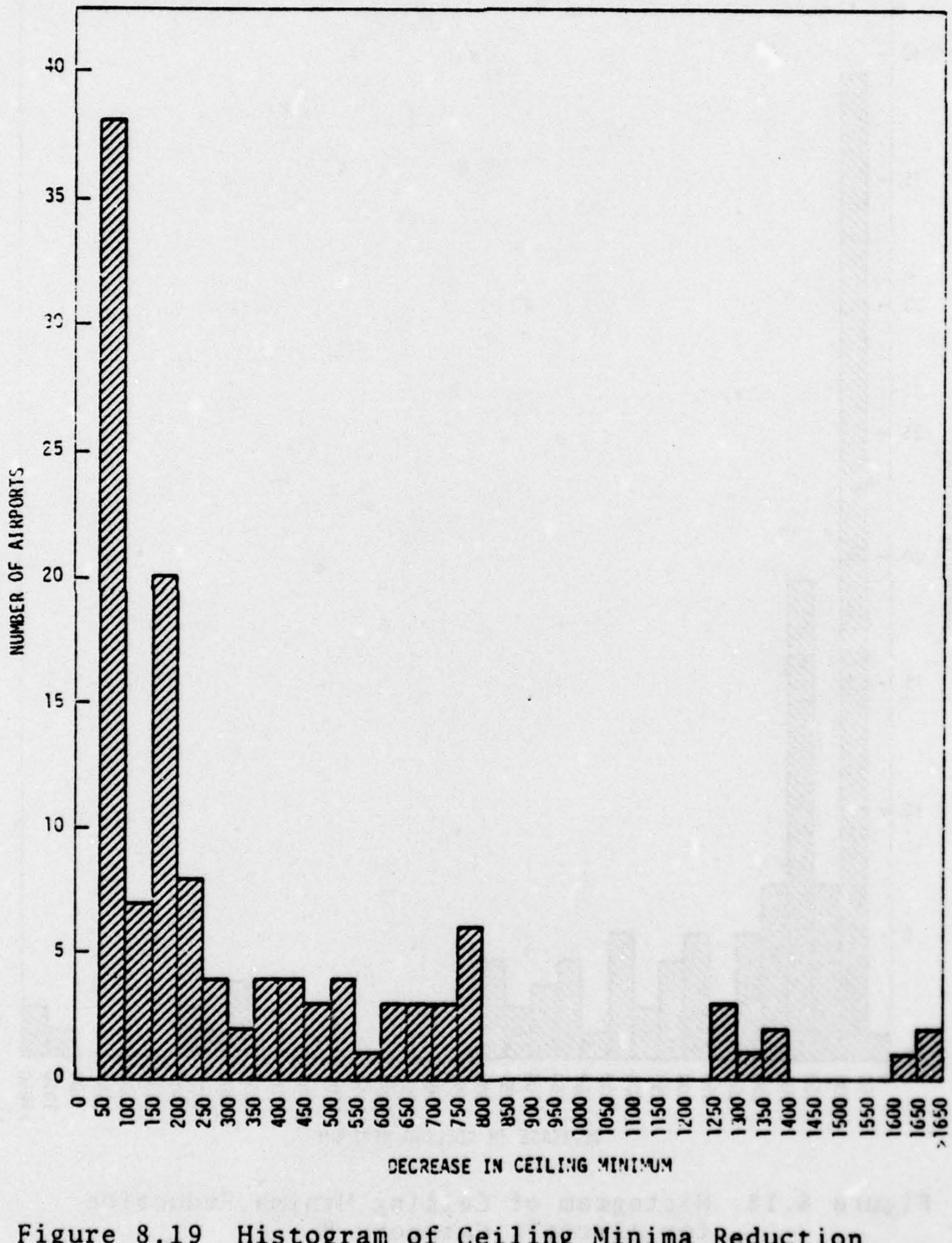


Figure 8.19 Histogram of Ceiling Minima Reduction for Aircraft Category C

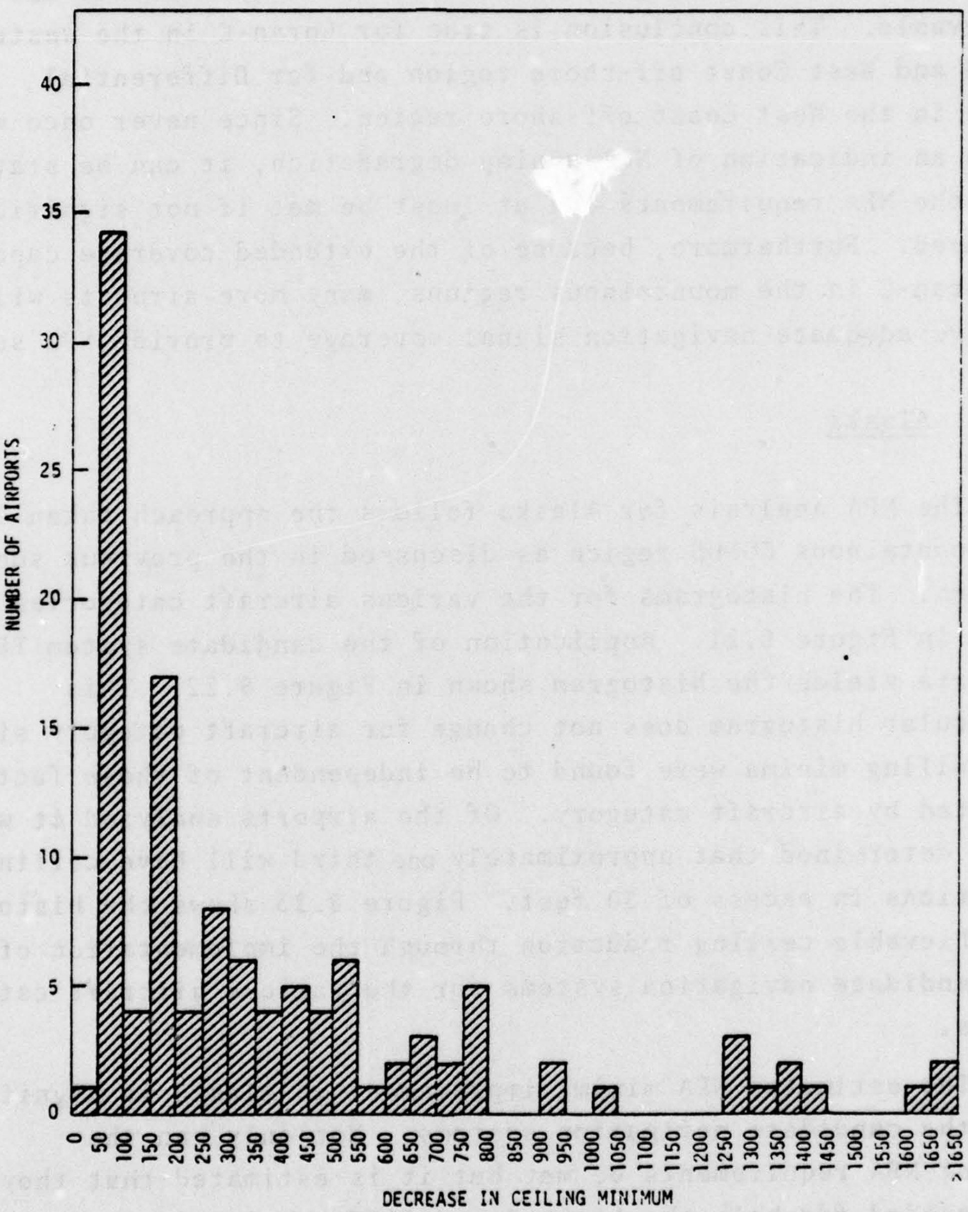


Figure 8.20 Histogram of Ceiling Minima Reduction of Aircraft Category D

In summary, it can be concluded that in the eleven western states of CONUS that significant NPA minima improvements are achievable. This conclusion is true for Loran-C in the western CONUS and West Coast off-shore region and for Differential Omega in the West Coast off-shore region. Since never once was there an indication of NPA minima degradation, it can be stated that the NPA requirements can at least be met if not significantly improved. Furthermore, because of the extended coverage capability of Loran-C in the mountainous regions, many more airports will receive adequate navigation signal coverage to provide NPA support.

8.3.3 Alaska

The NPA analysis for Alaska follows the approach taken in the mountainous CONUS region as discussed in the previous sub-section. The histograms for the various aircraft categories are shown in Figure 8.21. Application of the candidate system TERPS criteria yields the histogram shown in Figure 8.22. This particular histogram does not change for aircraft category since the ceiling minima were found to be independent of those factors affected by aircraft category. Of the airports analyzed it was again determined that approximately one third will have ceiling reductions in excess of 50 feet. Figure 8.23 shows the histograms of achievable ceiling reduction through the implementation of the candidate navigation systems for the various aircraft categories.

The estimated NPA minima improvement in Alaska is significant with the candidate navigation systems. Not only can the current NPA requirements be met but it is estimated that they will be exceeded for both the Loran-C and Differential Omega systems. Furthermore, the extended coverage capability of Loran-C and LF Differential Omega will provide NPA navigation signal support for a larger number of airports than are currently being serviced.

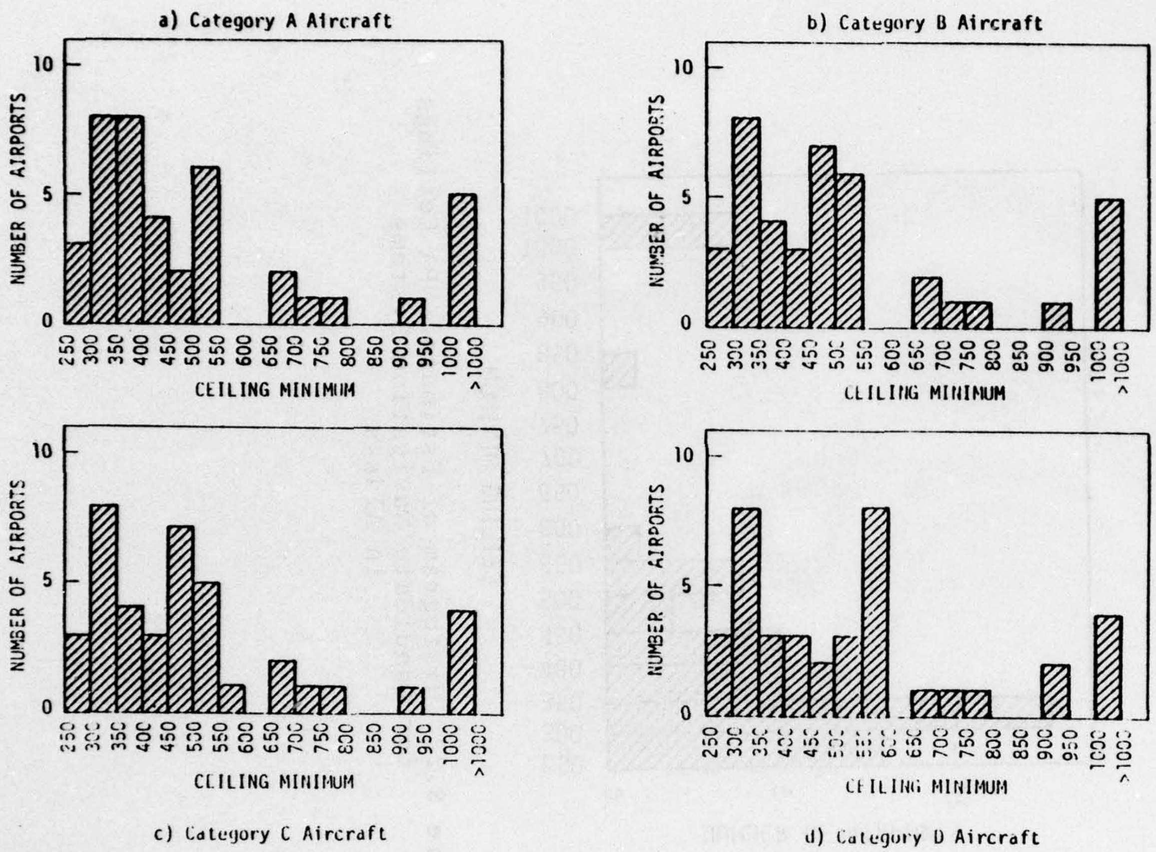


Figure 8.21 Histograms of Current NPA Ceiling Minima in Alaska

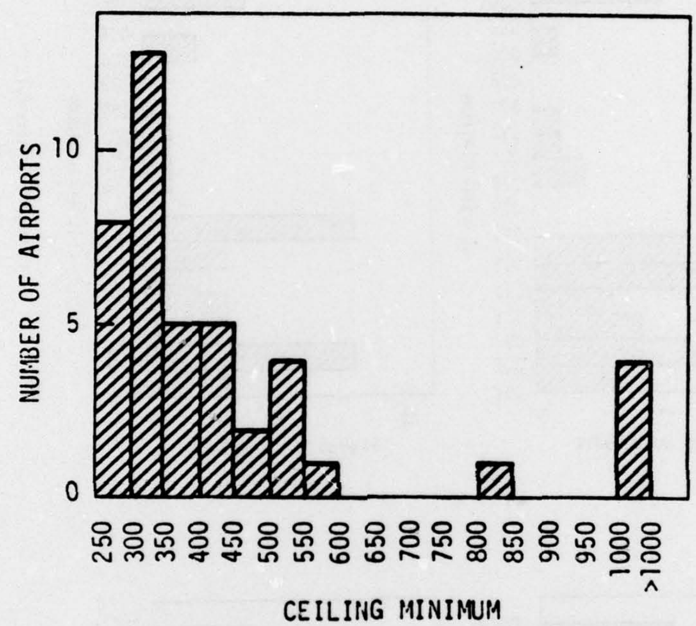


Figure 8.22 Histogram of Estimated NPA Ceilings for Candidate Navigation Systems in Alaska

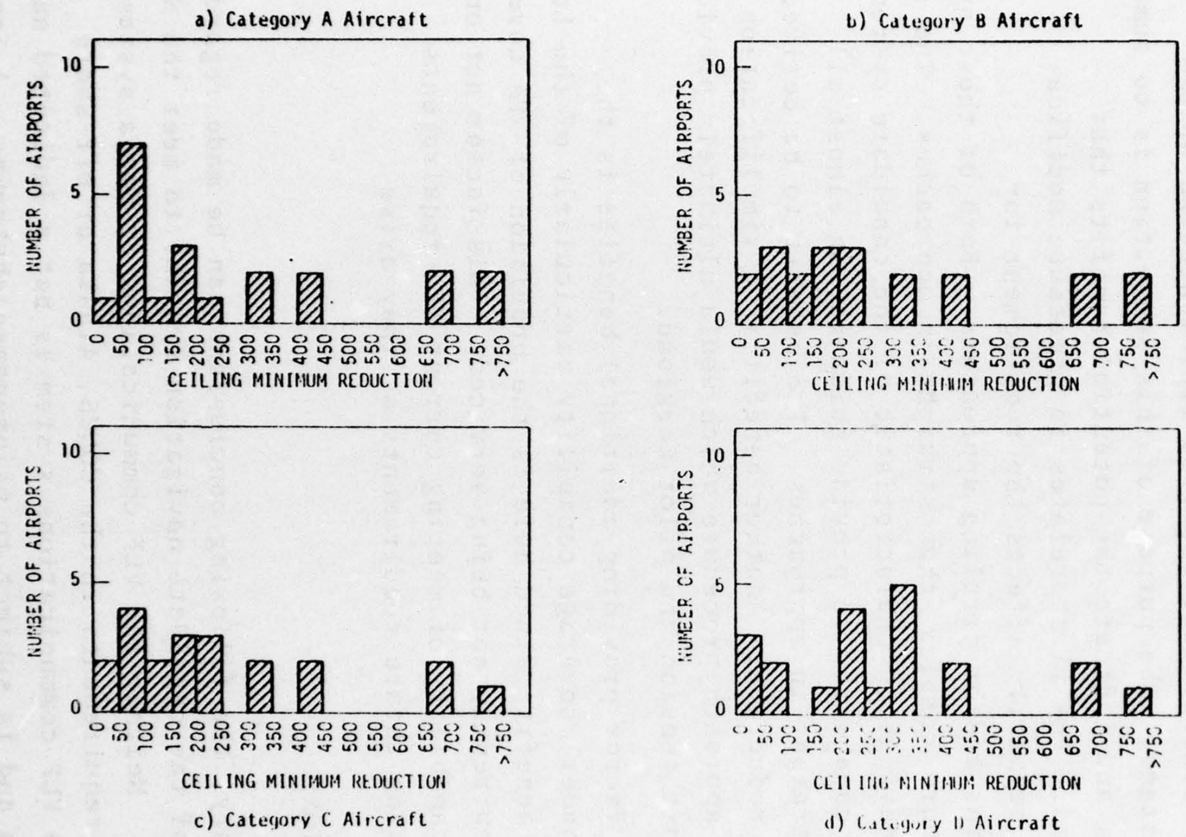


Figure 8.23 Histograms of Estimated NPA Ceiling Reductions in Alaska

8.3.4 Additional Factors

Throughout the analysis discussion in the previous subsections several additonal factors were identified which are manifested as benefits derived from implementation of the candidate systems. The purpose of this subsection is to summarize these factors and indicate the potential benefits that can be derived. The first relates to procedure modifications. This primarily affects the requirement for procedure turns and/or circling approaches. Both of these procedures are more complex than straight-in approaches. The inherent area navigation characteristic of the candidate systems provides the capability to provide guidance, in almost all cases, for straight-in approaches. The benefit to be derived is a ceiling reduction. Another benefit is a simplification of the final approach procedure which would ultimately provide reduced cockpit tension and pilot workload.

Another factor providing additional benefits is the extended (broader) coverage capability particularly of the Loran-C system. The benefit gained here is the provision of NPA coverage at airports currently not being serviced. This factor not only affects the capability of meeting current NPA requirements but also meeting future requirements as they arise.

8.4 CONCLUSIONS

In summary, the following conclusions can be made regarding the ability of the candidate navigation systems to meet the NPA requirements. Neither the VLF communications or Omega systems can meet the requirements in the CONUS, Alaska or off-shore regions. The VLF communications system is not a dedicated navigation system and is subject to maintenance shutdowns. A loss of signal coverage of this magnitude is intolerable. The Omega

navigation system lacks coverage over CONUS and CONUS off-shore in the Gulf of Mexico. In the remaining CONUS off-shore and in Alaska and Alaska off-shore the Omega system does not have sufficient accuracy to support NPA.

The lack of standard Omega coverage in CONUS and Gulf of Mexico region makes Differential Omega an unfeasible candidate for NPA. In Alaska, Alaska off-shore, and CONUS East Coast and West Coast off-shore regions, Differential Omega has been shown to at least meet the requirements if not provide improved performance. Similarily, Loran-C has been shown to exceed the NPA requirements in the CONUS, Alaska and Off-shore regions.

IX. CONCLUSIONS

The primary objectives of the study were met in that navigation requirements were specified for CONUS, Alaska, and Offshore and the capabilities of the Loran-C, Omega, Differential Omega and VLF communications signals were assessed toward meeting these requirements. The navigation system requirements are presented in terms of the following categories:

- Coverage
- Accuracy
- Operational Considerations
- Capacity
- Compabitility
- Signal Reliability

The navigation system evaluation for each of the systems is discussed below.

Based on the approved CCZ Loran-C configuration, coverage for Offshore and Alaska is complete except for the North Slope of Alaska area. One additional station would be required to complete the Alaska primary coverage. Given the additional three stations proposed for CONUS midcontinent, CONUS primary coverage would be complete. However, additional stations would be required for civil aviation use to meet redundancy requirements in all three areas. Estimates to meet the redundancy requirements for all three areas range from 19 to 23 more stations.

The demonstrated accuracy of Loran-C is 0.25 to 1.0 nm (RMS) absolute, and 300 feet(RMS)in repeatability. These accuracies are more than adequate to meet the requirement of all phases of civil aviation requirements under consideration.

The redundancy issue must be resolved before the system could be considered for civil air use as the primary navigation system. The principal problem is the large area, and potentially large number of aircraft, affected by the outage of a single transmitting station. However, the application of Loran-C as a supplementary system to fill the voids not covered by VOR/DME, particularly at low altitude, is more immediately viable. In either case, any increase in use by civil aviation will depend upon the availability of suitable low-cost avionics.

Omega was found to be an excellent candidate for Alaska and Alaska Offshore with good coverage from four to six of the eight stations, depending on time of year and day. Based on coverage, signal-to-noise ratios, and geometry, Omega can meet the enroute and low density terminal area requirements over the entire Alaska and Alaska Offshore region.

The final Omega system cannot be considered a candidate for CONUS. During midsummer and midday, a large part of the central CONUS will receive usable signals from only two stations with a region about the North Dakota station limited to only one station. Recent test data indicate that the coverage boundary for station F (Argentina) may not actually reach as far north as analytical predictions would indicate. This means that the Offshore area in the Gulf of Mexico may not be covered by more than two stations for much of the time.

The accuracy of Omega is nominally 1-2 nm (RMS). This is based on usable signals from three or more stations, the use of predicted phase corrections (PPCs), and reasonably good line-of-position (LOP) crossing angles. The LOP geometry over the Alaska and Alaska Offshore area is excellent providing further support to the viability of Omega for that region. The crossing angles of the principal LOPs over CONUS are notably less favorable.

The application of Differential Omega to the Alaskan, Alaskan Offshore, and CONUS Offshore requirement was evaluated. Differential Omega was not considered for the CONUS requirement because standard Omega coverage over CONUS is inadequate.

Differential Omega using LF or HF, (radio beacon frequency channels) was found to be a suitable candidate for the CONUS Offshore requirement on the East and West Coast. It was not considered for the Gulf of Mexico Offshore area because standard Omega coverage there is inadequate. VHF or other line-of-sight frequencies were not considered for the telemetry data link for Offshore because the line-of-sight range does not meet the coverage requirement. Since Loran-C has been approved for the CCZ maritime requirement and most of the stations are already implemented with the remainder to be completed by 1980, it is not likely that Differential Omega will be necessary or desireable for this requirement area.

For the Alaska and Alaska Offshore areas, Differential Omega was found to be a viable candidate for consideration. This is based on the excellent standard Omega coverage over the area. Standard Omega meets the enroute and low density terminal area requirements. The addition of Differential Omega will meet the non-precision approach requirements as well as provide greater accuracy throughout the Differential Omega coverage area. Eighteen (18) Differential Omega stations, based on using LF-HF (radio beacon frequency channels), are required for total coverage over the Alaska and Alaska Offshore areas. VHF and other line-of-sight frequencies for the telemetry data link are not considered viable because of the mountainous terrain and the Offshore range requirement.

The current and projected use of VLF communications signals for navigation over the areas of interest was investigated. Although some of the early navigation sets using VLF communications did not make use of other radio navigation signals, the current approach is to use VLF communications signals in conjunction with Omega signals. In view of recent agreements of understanding between the Naval Telecommunications Command and the FAA, this approach is sound and offers advantages which are not achievable separately. The combined signals provide a sufficiently redundant, stable, and synchronized radio grid about the globe to assure adequate useable signals anywhere at any time. The redundancy is particularly important because of the down times of individual stations for scheduled and unscheduled maintenance.

Based on geometry and signal-to-noise ratios, there should be at least four VLF communication stations providing useable signals at any location and time over the CONUS, Alaska, and Offshore areas which supplemented with Omega signals will provide adequate redundancy and useable geometry.

A potentially significant benefit offered by the candidate systems considered is the support of non-precision approach (NPA) requirements. This derives from the wide area and essentially all altitude coverage characteristics of the systems. The characteristics of the systems considered are much the same in regard to servicing non-precision approaches. For these reasons, a separate element of the study, which analyzed all systems considered, was devoted to this topic.

It was found, based on study results, that Loran-C exceeded the NPA requirements for the CONUS, Alaska, and Offshore regions. Flight test and other evaluation studies will be required to substantiate these results. Differential Omega could also meet the NPA requirements given that standard Omega coverage is available in the area of interest. Therefore, Differential Omega could support NPA requirements in Alaska, Alaska Offshore, East and West Coast CONUS Offshore, but

not CONUS mid-continent or Gulf of Mexico Off-shore. Standard Omega cannot support NPA requirements because of inadequate accuracy. VLF Comm by itself cannot be considered a candidate for NPA because the stations are not dedicated to navigation and are subject to unannounced signal interruptions.

Additional benefits that were found are derived from the inherent area navigation capability and availability of extended coverage from the candidate systems. The area navigation capability provides for simplification of the approach procedures from utilizing ceiling approaches and procedure turns to using simple straight-in approaches. Also, missed approach and curved approach guidance are available for obstruction avoidance. The extended coverage provides non-precision approach service at airports currently not receiving this service.

REFERENCES

1. "Federal Aviation Regulation, Part 91: General Operating and Flight Rules", Department of Transportation, Federal Aviation Administration, March 1974.

2. "Federal Aviation Regulation; Part 135: Air Taxi Operators and Commercial Operators of Small Aircraft", Department of Transportation, Federal Aviation Administration, November 1974.

3. "Federal Aviation Regulations, Part 121: Certification and Operations: Domestic, Flag and Supplemental Air Carriers and Commercial Operators of Large Aircraft", Department of Transportation, Federal Aviation Administration, April 1974.

4. "United States Standards for Terminal Instrument Procedures (TERPS)", Department of Transportation, Federal Aviation Administration, February 1970.

5. Clark, W.H., Bolz, E.H., Solomon, H.L., and Stephenson, A.R., "Implementation of Area Navigation in the National Airspace Systems" An Assessment of RNAV Task Force Concepts and Payoffs', Final Report FAA-RD-76-196, Systems Control, Inc., (Vt), Palo Alto, California, December 1966.

6. Stephenson, A. and Clark, W.H., "Area Navigation Route Width Requirements", Department of Transportation, Federal Aviation Administration, Systems Research and Development Service, Final Report, February 1976.

7. Cassell, R., "Area Navigtion High Altitude Payoff Analysis, Enroute Fast-Time Simulation Results", Federal Aviation Administration, Systems Research and Development Service, September 1975.

8. "Approval of Area Navigation Systems for Use in the U.S. National Airspace System", DOT/FAA Advisory Circular AC 90-45A, February 1975.

9. Halverson, A.G., et.al., "Area Navigation High-Altitude Network Study", Federal Aviation Administration, National Aviation Facilities Experimental Center, Final Report FAA-RD-76-6, February 1976.

10. McConkey, E.D., "Terminal Area Design, Analysis and Validation of Task Force Concepts", Champlain Technology Industries, Division of Systems Control, Inc. (Vt), Final Report, October 1975.

11. Maurer, J., et. al., "Preliminary Two-dimensional Area Navigation Terminal Simulations", Federal Aviation Administration, National Aviation Facilities Experimental Center, Report, RD-74-209, October 1974.

12. Crimbring, W., and Maurer, J., "Area Navigation/Vertical Area Navigation Terminal Simulation Results", Federal Aviation Administration, National Aviation Facilities Experimental Center, Draft Final Report.

13. Bolz, E.N., Scott, R., Stephenson, W.R., and Heine, W., "Systems Integration: RNAV and the Upgraded Third Generation System", Preliminary Draft Report, Systems Control, Inc. (Vt), August 1976.

14. Adams, R.J., "Area Navigation Waypoint Designation Standards", Final Report FAA-RD-75-122, Systems Control, Inc. (Vt)., July 1974 (published August 1975).

15. Adams, R.J., "Preliminary RNAV Avionics Standards (2D and 3D Area Navigation Systems", Final Report FAA-RD-75-178, Systems Control, Inc. (Vt), July 1974 (Published, November 1975).

16. Frenkel, G., et cal, "Radio Navigation Study, Vol.I and Vol.II", Final Report AD-A010 114, Computer Sciences Corporation, Falls Church, Virginia, February 1975.

17. Rowland, W.F., (editor) Wild Goose Association Radionavigation Journal 1976, Wild Goose Association, Inc., Action, MA 01720

18. McConkey, E.D., "Terminal Area Design, Analysis and Validation of RNAV Task Force Concepts", FAA-RD-76-194, October, 1976.

19. Maurer, J., et al., "Preliminary Two Dimensional Area Navigation Simulation", Report No. FAA-RD-74-209, DOT-FAA-NAFEC, February 1975.

20. Johler J.R., and Berry L.A., "Loran-D Phase Corrections Over Inhomogeneous, Irregular Terrain, Report No. IER59-ITSA56, DOC-ESSA-ITSA, November 1967.

21. J.R. Johler, W.J. Kellar, and L.C. Walters, "Phase of the Low Radio frequency Ground Wave", National Bureau of Standards Circular 573, U.S. Dept. of Commercen Washington, D.C. June 26, 1956.

22. Hughes, M. and Adams, R.J., "An Operational Flight Test Evaluation of a Loran-C Navigator", prepared by the Champlain Technology Division of Systems Control, Inc., West Palm Beach Florida, for the Department of Transportation, U.S. Coast Guard, November 1976.

23. Johler, J.R. and Horowitz, S., "Propagation of a Loran Pulse Over Irregular, Inhomogeneous Ground," Electromagnetic Wave Propagation Involving Irregular Surfaces and Inhomogeneous Media, Advisory Group for Aerospace Research and Development (AGARD), Paris, France, February 1975.

24. Anderson, C.W., III, et al, "Coastline Induced Loran-C Anomalies", U.S. Army ECOM, Fort Monmouth, N.J., February 1973.

25. Anderson, C.W., et al, "Description of a Loran-C Propagation Anomaly and Associated Coordinate Conversin Problems", U.S. Army ECONM, Fort Monmouth, N.J., December 1971.

26. Eggers, T.H., "AN/GRM-99 Loran/Inetial Simulator Validation Report on the Second Phase Test REsults", Mitre Technical Report No. MTR-3093 prepared for USAF-ESD at Eglin AFB, Florida, June 1975.

27. Scott, R.E., "Hyperbolic System Instrumentation Techniques", Modern Navigation Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conferences, Ann Arbor, Michigan, July 1968.

28. "LSI-AN/ARN-101 Navigation and Weapon Delivery System", Confidential Report, ADTC-TR-75-54, Vol I, USAF-ADTC, Eglin AFB, Florida, Nov. 1975.

29. Hamilton, J.R. "Loran-C Cycle Matching Operational Evaluation in the North Pacific Area", Final Report FAA-RD-75-142, Continental Airlines, Inc. Los Angeles, California, October 1975.

30. "International Standards and Recommended Practices, Aeronautical Telecommunications, Annex 10 to the Convention on Inernational Civil Aviation", Montreal, Quebec, Canadad.

31. "IFR Aircraft Handled, Forecast by Air Route Traffic Central Center, Fiscal Years 1975-1986", DOT-FAA, September 1974.

32. Goodman, G.R. and Oswitt, R.P., "Loran-C Replacement Equipment (LRE)", Navigation: Journal of the Institute of Navigation, Vol. 23, No.3, Fall 1976.

33. Joglekar, A., et al.., "Evaluation of Loran-C for Domestic Air Navigation", Mitre Metrek Divsion, MTR-7180, October 1976.

34. Burgess, B., Walker, D., "Omega Errors Due to Propagation Variations", Royal Aircraft Establishment Technical Report 69194, September 1969.

35. "Proceedings of the First Annual Meeting of the International Omega Association", International Omega Association, Box 2324, Arlington, VA 22202, July 1976.

36. Clark, G.P., "Simplified Determination of the Ellipse of Uncertainty", Vol. 21, No.4, Journal of the Institute of Navigation, Winter 1974 - 1975.

37. Swanson, E.R. "VLF Navigation Monitor: Purpose and Function", Report FA74WAI-425-4, NELC TR 1955, Naval Electronics Laboratory Center, San Diego, California, May 1975.

38. "Investigation of the Propagation of Omega Very Low Frequency Signals and Techniques for Improvement of Navigation Accuracy Including Differential and Composite Omega", Final Report, NASA CR-132276.

39. "Differential Omega Test and Evaluation Program", Final Report, TRACOR 67-135-U, TRACOR, Austin Texas, Janaury 1967.

40. Karkalik, F., and Wischmeyer, E., "An Operational Evaluation of Omega for Civil Aviation Oceanic Navigation", Final Report, FAA RD-77-65, Systems Control, Inc. (Vt), Palo Alto, California, February 1977.

41. Swanson, E.R. and Davey, J. "Differential Omega Evaluation", Technical Note 187, NOSC, San Diego, California, April 1977.

42. "Minimum Operational Characteristics and Minimum Performance Standards for Airborne Omega Receiving Equipment," Final Draft, RTCA Paper No. 17-76/SC126-40, Washington, D.C., February 1976.

43. Swanson, E.R., Adrian D.J, and Levine, Ph.H., "Differential Omega Navigation for the U.S. Coastal Confluence Region, Part II: Requirements, Accuracies and System Definition", NELF Report TR F105, San Diego, California, Jan. 1974

44. Simolunas, A.A. and Quinn, G.H., "Alaskan Air Navigation Requirements - Vol. I, Overview", Final Report, FAA-RD-76-27, I, Washington, D.C., January 1977.

45. Solomon, H.L., Heine, W., Stephenson, A.R. and McConkey, E.D., "Alaskan Air Navigation Requirements, Vol. II - Near Term Benefits Analysis of the Alaskan Air Navigation System", Final Report, FAA-RD-76-27, II, Systems Control, Inc., (Vt), Palo Alto, California, January 1977.

46. Heine, W., "An Avionics Sensitivity Study, Vol. II, Evaluation of Airborne Navigation System Performance During RNAV/MLS Transition", Final Report, NASA CR-145108, Systems Control, Inc. (Vt)., Palo Alto, California, September 1976.

47. Amoroso, Frank and Kivett, James A., "Simplified MSK Signaling Technique", IEEE Transactions on Communications, April 1977, pp 433-446.

48. Letter from Commander, Naval Telecommunications Command, Department of the Navy to Director, Flight Standards Service, Federal Aviation Administration, 8 Sept. 1976.

49. Tymczyszyn, William R., "Inflight Worldwide VLF Experience Using Global Navigation GNS-500", Global Navigation Incorporated, Torrance, California, Company Publication.

50. Letter from James E. Dow, Acting Administrator, FAA to the Honorable Frank A. Shrontz, Chairman, DOD Advisory Committee on Federal Aviation, Department of Defense, April 25, 1975.

51. Letter from Frank A. Shrontz, Chairman, DOD Advisory Committee on Federal Aviation, Department of Defense to Mr. Dow, Acting Adminstrator, FAA, 30 June 1975.

52. Notice 8110.24, Subject, Omega/VLF Navigation Equipment for Domestic, Including Alaska Use, Enroute only.

53. Supplemental Type Certificate, Number SA3192WE, Department of Transportation, Federal Aviation Administration, May 14, 1976.

54. Communications Components Corporation, ONTRAC-II Navigation System, Company Publication.

55. Swanson, E.R. and Dick, M.J., "Propagational Assessment of VLF Navigation Signals in North America and the North Atlantic", Report Number FA74WAI-425-2, Federal Aviation Administration, 4 February 1975, performed by Naval Electronics Laboratory Center.

56. "Jeppessen Approach Chart", Revision 20, Vol.4, Jeppessen Sanderson, Inc., Denver, Colorado, May 1977.